COLD CATHODE TUBES

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Preface

Although semiconductor devices are becoming more and more widely used in all types of electronic equipment, cold cathode tubes are nevertheless retaining their importance for a very wide variety of applications. It is the aim of this book to present the student with a general account of the functioning of the various types of cold cathode tube and of the types of circuit in which these tubes are normally used.

A reasonable knowledge of basic physics is assumed together with some familiarity with common electronic components. Whilst the approach is largely non-mathematical, a simple account of the basic theory of the gas discharge has been included in the first chapter to introduce the student to ideas which he is likely to meet in further reading. However, this section may be omitted by those readers who are interested only in the practical aspects of cold cathode tube circuitry. Each of the chapters is reasonably complete in itself and may be understood by those who have some knowledge of the material in Chapter 1.

The types of tube discussed in this book are those which are conventionally regarded as cold cathode tubes. Although photocells undoubtedly have cold cathodes, they have not been included, since it is felt that they are a rather different type of tube which are not generally placed in the cold cathode category. Although the temperature of the cathode of an arc discharge tube can be quite high, this type of tube is nevertheless regarded as a cold cathode tube. A very brief discussion on gas lasers and on the use of flash tubes in ruby lasers has been included in order to introduce the student to these important and relatively new devices. A few very elementary experiments with neon diodes and trigger tubes have been included at the end of Chapters 2 and 3.

Alcester, 1967   J.B.D.

Acknowledgements

Introduction
THE RANGE OF COLD CATHODE TUBES AND THEIR APPLICATIONS

Some of the earliest types of cold cathode tube were developed about 1856 by H. Geissler. He employed tubes of several inches in length filled with a gas such as air or hydrogen at a pressure of a few millimetres of mercury. A very high voltage was applied between two metal electrodes situated at each end of the tube so that light was emitted. Very large neon discharge tubes were developed about 1910; this created interest in the possibility of using cold cathode tubes for lighting purposes instead of the conventional tungsten filament lamp, since it was felt that an economical cold cathode lamp might be produced which would consume little current. However, the present uses of cold cathode tubes for lighting are mainly in advertising and in applications where a relatively small amount of light is required.

Small cold cathode diodes can be used for counting electrical pulses, for carrying out logic and timing operations, as relaxation oscillators, etc., but trigger tubes are often preferred for these purposes. Trigger tubes have a separate trigger electrode to which an input can be applied when it is desired to initiate a discharge between the main anode and the cathode. Trigger tubes can replace transistors and thermionic valves in many types of switching circuit if the speed of operation need not be extremely high.

One of the main uses of gas filled diodes is for voltage stabilisation. A wide range of glow tubes is available for the stabilisation of potentials of up to some hundreds of volts when the load current variations do not exceed some tens of milliamps. Voltage stabiliser circuits can also be designed using trigger tubes. Corona discharge tubes can be employed to stabilise potentials over a range of about 350 to 30,000 V, but the permissible variations in the output current are much smaller than in the case of glow stabiliser tubes. Cold

cathode tubes can be used in conjunction with thermionic valves for obtaining a very high degree of voltage stabilisation even if there are wide variations in the load current.

Cold cathode counting tubes are multi-electrode tubes in which each input pulse causes a glow discharge to step one position in the tube to another electrode. The position of the glow in the tube indicates the number of pulses which have been counted. A single decade tube can indicate a maximum of nine counts, but further tubes may be used to count the number of tens, hundreds, etc.

The cathodes of numerical indicator tubes are shaped in the form of digits. When a current is passing to any one of the cathodes, the glow in the gas is in the shape of the digit, which is thus clearly indicated. Such tubes can be used to indicate the state of the count in a counting circuit or the voltage being measured by a digital voltmeter, etc. Other tubes are available for the indication of various symbols or letters of the alphabet instead of digits.

The most commonly used type of nuclear radiation detector is the Geiger-Müller tube. This provides large output pulses each time ions are formed in the gas by a particle of the incident radiation. Other types of cold cathode nuclear radiation detectors are important for some applications.

Arc discharge tubes are used as flash tubes to provide light pulses of short duration for photography, for stroboscopic work, for the operation of ruby lasers, etc. Other types of arc discharge tube have been designed for switching high voltages at high currents; they are often used for protecting equipment against overloads. Gas lasers operating from radio frequency power are cold cathode tube assemblies which provide an intense beam of coherent radiation.

Most cold cathode tubes have a reliability and life quite comparable with that of modern semiconductor devices when they are used in correctly designed circuits. They are especially useful in simple industrial circuits where simplicity and economy are more important than miniature size. Cold cathode tubes have the disadvantage that a fairly high power supply voltage is required for their operation, but they can be made with close tolerance characteristics which are not very dependent on the operating temperature.

Most gas filled tubes (other than those designed for the detection of nuclear radiation) are devices which are either in the fully conducting or the non-conducting state at any given instant; they may therefore be referred to as 'On/Off' devices. They cannot be used to amplify sine waves or irregular waveforms, since they have no state of partial conduction. Neither can they operate at very high frequencies. For these reasons they are not normally found in domestic radio or television equipment.

1
Fundamental Principles

In all types of electronic tube an electric current passes either through a vacuum or through a gas. A current can be carried only by the movement of charged particles such as electrons, charged atoms, etc. These charged particles, which are known as ions, are not normally present in a vacuum or in a gas, although they may be created in various ways. In the absence of artificially produced ions, a vacuum or a gas is virtually a perfect insulator.

ELECTRON EMISSION AND WORK FUNCTION

All substances contain electrons, but these electrons cannot leave a material and pass into the surrounding space unless they are given energy. The amount of energy required to release an electron from a surface depends on the material of the surface concerned. The work function of a substance is defined as the energy which must be given to an electron to enable it to leave the substance. Work functions are conveniently expressed in electron volts. An electron volt is the work done in moving an electron between two points which differ in potential by one volt. A material of low work function can be made to emit electrons easily, but a material of high work function will emit electrons only with difficulty. The way in which an electron acquires the energy it needs to leave an electrode varies in different types of electronic tube.

Tubes which employ hot cathodes are known as thermionic tubes. The common thermionic valves, as used in radio and television receivers, employ heated cathodes in a high vacuum. At the high temperature of the cathode there is a certain probability that an electron near to the surface of the cathode will gain enough

energy to enable it to leave the cathode and travel to one of the other electrodes. Cathodes of a moderately high work function (e.g. tungsten with a work function of 4·54 eV) must be heated to a brilliant white heat (about 2,200°C) before they emit many electrons. However, cathodes of low work function (e.g. nickel coated with a mixture of barium and strontium oxides) will emit electrons at a dull red heat, since the energy an electron must acquire in order to leave such a cathode is only about 1 eV.

Photocells employ cathodes coated with a material of a fairly low work function. When light falls onto the cathode, the energy of the light is given to the electrons of the cathode material and some of these electrons leave the cathode ('photoemission'). In a vacuum photocell these electrons constitute the total current flowing through the tube. In a gas filled photocell the electrons emitted from the cathode knock further electrons from the atoms of the gas with which they collide ('gas amplification').

According to the quantum theory, light may be considered to consist of particles which are known as photons. Each photon has an energy $h\nu$ where h is a universal constant known as Planck's constant and ν is the frequency of the light. Thus the energy of the photon is proportional to the frequency of the light. A photon of blue light has more energy than a photon of red or yellow light, but not so much energy as a photon of ultra-violet radiation.

In photoemission processes the energy of a single photon may be given to one electron of the cathode material. Thus photoemission can occur only if the energy of the photon exceeds the work function of the cathode surface. Ultra-violet light will cause photoemission from surfaces of low and of moderately high work functions, but red light will cause photoemission only from cathodes of very low work function. Even infra-red light will cause photoemission from a surface of caesium on silver oxide. Visible light will not cause photoemission from surfaces which have a work function greater than about 3 eV.

Most types of cold cathode tube are filled with an inert gas at a pressure much below atmospheric. Tubes for detecting nuclear radiation (such as Geiger-Müller tubes) pass a small current pulse for a short time when ions are created in the tube by the radiation. As the electrons formed by the radiation move towards the electrodes, they may create further ions when they collide with molecules of the gas, but the discharge ceases when the radiation no longer falls on the tube.

In many types of gas filled tube the discharge is self sustaining. In this case ions formed in the tube initiate the discharge, but then the bombardment of the cathode by the positive ions moving under

the influence of the electric field results in enough electrons being emitted from the cathode to maintain the discharge. A self sustaining discharge is, therefore, not affected if the external supply of ions ceases. The current will continue to flow until the applied potential is reduced to such a value that the discharge is no longer self maintaining.

GAS DISCHARGES

The conduction of electricity through gases is complicated by the very wide variety of processes which can occur. The following discussion is a very much simplified account. It is suggested that those requiring further details of the basic phenomena occurring in gas discharges should consult some of the works listed at the end of this chapter.

An electric current will pass through a gas only if there are ions present in the gas when a potential difference is applied between the electrodes. A very small number of ions are formed intermittently in any gas by the passage of cosmic rays and by the particles emitted from stray radioactive atoms which are present in all materials. However, in many gas filled tubes it is necessary to employ a method of injecting ions into the gas artificially.

GAS AMPLIFICATION

An electron moving towards the anode will lose only a very small fraction of its energy in collision with a gas molecule, since its mass is so much smaller than that of a gas molecule. Electrons merely bounce off gas molecules with little loss of energy. Thus the energy acquired by an electron from the electric field can accumulate until it reaches a value known as the ionisation energy of the gas; the electron can then remove an electron from a molecule of the gas. Although the incident electron and the liberated electron now have little energy, they are accelerated by the electric field and give rise to further ions. The process by which the number of ions is increased is known as gas amplification or gas multiplication.

Positive ions moving towards the cathode cannot move far before they strike a gas molecule. As the two colliding particles have very similar masses, an ion will normally lose a considerable fraction of its energy when it collides with a gas molecule. In successive collisions the kinetic energy of an ion is shared with a number of gas molecules. Thus positive ions cannot acquire an appreciable

amount of energy unless the mean free path is large (i.e. unless the gas pressure is low). Positive ions do not, therefore, normally give rise to gas amplification.

Although gas amplification results in an increased current flowing through a gas discharge tube, it cannot alone render a discharge self sustaining, since all of the electrons formed by gas amplification quickly reach the anode. It is electron emission from the cathode under positive ion bombardment which can result in a discharge becoming self sustaining. Some photoemission from the cathode may also occur, but positive ion bombardment is normally a much more important effect.

TYPES OF DISCHARGE

Various types of discharge can occur between two electrodes in a tube filled with a gas at a pressure of a few millimetres of mercury. The main types, in order of increasing current, are known as the Townsend discharge, the normal glow discharge, the abnormal glow discharge and the arc discharge.

The voltage/current characteristic of a gas discharge tube under various conditions may be represented by the type of graph shown
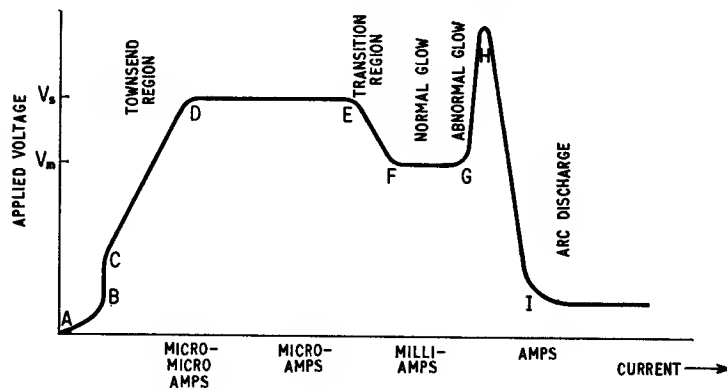

Fig. 1.1. The variation of voltage with current in a gas discharge.

in Fig. 1.1. The exact form of this graph depends on the tube geometry, on the gas pressure and on the nature of the gas. The current is plotted on a scale which is approximately logarithmic, since currents ranging from about 10^{-18} A to over 10 A must be accommodated on the graph. If a linear scale were used, the

left-hand part of the graph would be compressed so much that this part would not be visible.

If ions are injected into the gas at a constant rate, the current passing first increases with the applied voltage (A to B in Fig. 1.1). In this region an increase in the applied potential causes the ions to move to the electrodes more quickly and hence reduces the chance that an ion will be neutralised by an ion of the opposite charge before it reaches the electrode. When the applied potential reaches the point B, virtually all of the ions reach the electrodes. An increase of the applied potential in the region B to C does not, therefore, cause an appreciable increase in the current flowing. Gas amplification occurs when the applied potential exceeds that at point C. An increase in the applied potential increases the gas amplification factor and hence the current flowing.

As the applied potential is further increased, a point is reached at which the so called breakdown occurs. Under these conditions an electron leaving the cathode will, on an average, cause at least one further electron to be formed at the cathode by ionic bombardment. Thus the system is effectively one of positive feedback and the current increases rapidly.

In the transition region from E to F the incremental resistance is negative. Any increase in the current passing through the tube will result in a decrease in the voltage across the tube; owing to the internal resistance of the voltage supply, this will result in a further increase in the current flowing. Thus the transition region is unstable and the operating point moves very quickly into the region of the normal glow (F to G in Fig. 1.1).

In practice this means that as soon as the applied potential reaches a certain value known as the striking, starting or ignition voltage (V_s in Fig. 1.1), the current increases from a value of perhaps 10^{-14} A to some milliamps. This process is known as breakdown, ignition or firing. Immediately after breakdown has occurred, the voltage across the tube falls from the striking voltage to a value known as the maintaining, burning or running voltage (V_m in Fig. 1.1).

The voltage across the tube shows only a very small change as the current is increased from F to G in the normal glow region of the characteristic. Thus the position of the operating point cannot be controlled by the inter-electrode voltage, but is determined by the current flowing through the tube. This current is limited by a resistance placed in series with the tube; in the absence of such a resistance the current will increase and the tube is likely to be permanently damaged.

A further increase in current will result in the operating point moving into the abnormal glow (or anomalous glow) region of the

characteristic where the voltage across the tube increases with the current flowing (G to H in Fig. 1.1).

ARC DISCHARGE

Still higher currents will cause the discharge to pass through a second negative resistance region marked H to I in Fig. 1.1. Hence it quickly moves to the arc discharge region where the current exceeds that at the point I. In an arc discharge the voltage across the tube is typically about 20 V and is more or less independent of the current flowing between the electrodes. The current density in an arc discharge is usually of the order of some hundreds of amps per square centimetre, the cross sectional area of the discharge being proportional to the current flowing.

In an arc discharge the cathode may become so hot under intense ionic bombardment that thermionic emission occurs and gives rise to the self-sustaining arc discharge. Such high temperature arcs may be struck between carbon rods and temperatures of the order of 3,000°C can be reached. It appears that a different process occurs in the case of arcs employing a cathode of mercury or certain other non-refractory substances, since the metal would boil at temperatures very much lower than those needed for thermionic emission. It is believed that field emission occurs in such cases; that is, electrons are drawn from the cathode under the influence of an extremely high local electric field. Such arcs may be referred to as low temperature arcs. In a high temperature arc the discharge remains at one point on the cathode, but in a low temperature arc it moves continuously over the surface of the cathode.

Gas filled tubes which operate in the normal glow, abnormal glow or arc discharge regions of the characteristic emit light during their operation. The light is emitted by excited atoms giving up their energy. A very small amount of light is emitted even before breakdown occurs.

THE NORMAL GLOW

Most types of cold cathode tube operate in the normal glow region. The mechanism of conduction in this region will now be considered in more detail.

In the Townsend region of the gas discharge the current is very small and there are relatively few charged particles to distort the electric field. The potential gradient between the electrodes is,

therefore, almost uniform in a tube employing parallel plate electrodes. In the normal glow region, however, there is a much steeper potential gradient near to the cathode of the tube than elsewhere. This arises because the positive ions formed in the discharge move much more slowly than the electrons owing to their greater mass. This results in an excess of positive ions being present at a short distance from the cathode. This excess of positive ions acts as a positive space charge or virtual anode which distorts the electric field strength, increasing it in the region of the cathode. The steep potential gradient near to the cathode increases the efficiency of ionisation and enables the maintaining voltage of the tube to be lower than the striking voltage.

In the normal glow region of the characteristic almost the whole of the potential difference applied between the electrodes appears near to the cathode. It is known as the cathode fall of potential or merely as the cathode fall. It is not present in thyratron tubes which are gas filled tubes with heated cathodes.

Breakdown occurs in a tube when the increasing current gives rise to an increasing space charge which results in a steeper potential gradient near to the cathode; this in turn gives rise to more ions and hence a still larger current. This process, which is a kind of positive feedback, continues until the potential distribution in the tube is most favourable for efficient ionisation.

In the normal glow region of the characteristic the area of the cathode which is covered by the glowing gas increases with the current passing through the tube. The cross sectional area of the discharge automatically adjusts itself so that the potential distribution in the cathode region leads to the maximum ionisation efficiency. This is the condition for a minimum value of maintaining voltage. The current density, however, is dependent on the gas pressure.

When the cathode is completely covered by the glow, any further increase in the current passing through the tube will result in the operating point moving into the abnormal glow region of the characteristic. Maximum ionisation efficiency can then no longer occur. Thus the potential difference across the tube rises in the abnormal glow region.

The appearance of a glow discharge may be similar to that of Fig. 1.2, but it will vary widely with the gas pressure, the tube geometry, etc. The positive column may be striated and may be faint or quite bright. The Crookes dark space (also known as the cathode dark space) is shorter than the Faraday dark space. The cathode glow, which is hardly noticeable, is probably caused by excitation of gas molecules under positive ion bombardment.

If the length of the discharge is reduced by moving the anode nearer to the cathode, the positive column will be reduced in length until it disappears entirely when the anode enters the Faraday dark space; the remainder of the discharge will not be appreciably affected. The voltage across the tube remains fairly constant until the anode enters the Crookes dark space, when the potential difference across the tube rises sharply. The cathode fall of potential
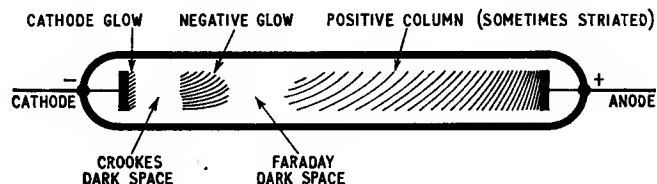

Fig. 1.2. *The regions of the glow discharge.* (*The glowing parts are shown shaded.*)

occurs across the Crookes dark space where the positive space charge is present. It is in this region that the electrons are accelerated to such a velocity that they can cause gas amplification. It is, therefore, not surprising that the voltage required to maintain the discharge rises when the anode enters this dark space; the process which maintains the discharge takes place in the Crookes dark space. The length of this dark space is inversely proportional to the gas pressure.

The gas contains approximately equal numbers of electrons and positive ions at all points except in the Crookes dark space; such an ionised gas is known as a plasma. The plasma is a good conductor of electricity, since it contains many mobile electrons.

For flat electrodes separated by a distance d in a pure inert gas of pressure p, the striking voltage, V_s, is a function of the product dp (Paschen's Law). Typical Paschen curves are shown in Fig. 1.3 for pure argon, pure neon and for a mixture of argon and neon. It can be seen that a small amount of an inert gas mixed with another inert gas can have a considerable effect on the ionisation of the latter (the Penning effect). The gas which is the main constituent of the mixture is raised to metastable energy levels in the discharge; atoms in such energy levels do not immediately lose their energy by photon emission. If the added gas has a lower ionisation energy than the metastable levels of the main constituent, the metastable atoms give up their energy to the added gas which is thus ionised. The striking voltage is, therefore, less than it would be with either of the gases in the pure form. Such mixtures are known as 'Penning mixtures'. Neon, for example, has a metastable energy level of

16.6 eV, whilst argon has an ionisation potential of 15.6 eV. Penning mixtures are used as the gas filling in many types of cold cathode tube other than stepping tubes.

The presence of small quantities of most contaminating gases often has an effect similar to that of argon, since their ionisation potentials are likely to be less than the metastable energy levels of neon. The addition of some argon to the neon in a tube will therefore result in the presence of contaminating gases having a much smaller effect on the characteristics of the tube concerned than if neon alone were used.

The Paschen curves show that there is a minimum value of the striking voltage as the pressure or the inter-electrode distance is
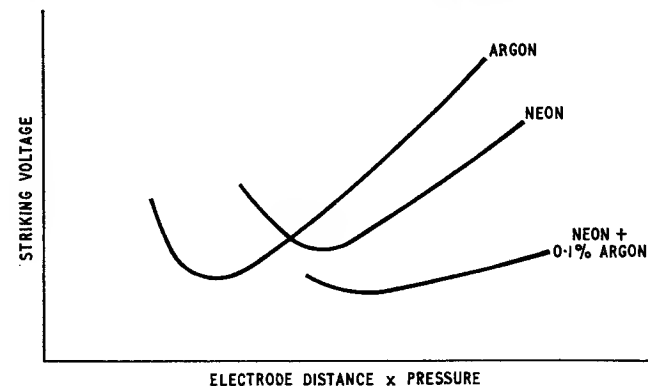

Fig. 1.3. *Some Paschen curves.*

changed. At high pressures a charged particle loses much energy to gas molecules, whilst at low pressures the number of ionising collisions are relatively few. Similarly at large inter-electrode distances the number of collisions occurring as a charged particle passes from one electrode to the other will be large, whereas at very low distances they will be few for a specified gas pressure. Thus there is an intermediate value of the product of inter-electrode distance and gas pressure at which the ionisation efficiency is a maximum. This corresponds to the minimum of the Paschen curve.

BASIC THEORY OF THE SELF SUSTAINING DISCHARGE

Let η be the average number of ion pairs produced in a gas by an electron falling through a potential difference of one volt. (η is known as the ionisation coefficient or the first Townsend coefficient.)

Let N be the number of electrons present at a point in the tube where the potential is v volts above the cathode potential.

$$\mathrm{d}N = N\eta\,\mathrm{d}v$$

$$\int \frac{\mathrm{d}N}{N} = \int \eta\,\mathrm{d}v$$

Let us assume initially that the value of η is constant. In this case one obtains by integration:

$$\log_e N = \eta v + C$$

If one considers the case where one electron leaves the cathode, at the cathode $v = 0$ and $N = 1$. Hence $C = \log_e 1 = 0$.

$$\log_e N = \eta v$$
$$N = e^{\eta v}$$

Thus the total number of electrons reaching the anode for each electron leaving the cathode is equal to $e^{\eta V}$ where V is the potential across the tube. The number of ion pairs created is one less than this number, namely $(e^{\eta V} - 1)$, since one electron entered the gas initially.

Each electron leaving the cathode gives rise to an average of $(e^{\eta V} - 1)$ positive ions which strike the cathode. Let a positive ion incident on the cathode produce an average of γ emitted electrons. (γ is known as the secondary emission coefficient or the second Townsend coefficient.) Thus the $(e^{\eta V} - 1)$ positive ions arising from a single electron will give rise to an additional $\gamma(e^{\eta V} - 1)$ electrons by ion bombardment. The discharge becomes self sustaining when one electron leaving the cathode produces on an average at least one further electron from the cathode. This limiting condition occurs when

$$\gamma(e^{\eta V_s} - 1) = 1$$

where V_s is the striking potential of the tube.

At breakdown

$$e^{\eta V_s} \gg 1$$

Hence the approximate condition for the discharge to be self sustaining

$$\gamma\,e^{\eta V_s} \simeq 1$$

Thus the minimum potential which must be applied to cause breakdown, V_s, is given by the equation

$$V_s \simeq \frac{1}{\eta} \log_e \frac{1}{\gamma} \tag{1.1}$$

or

$$V_s \simeq \frac{-1}{\eta} \log_e \gamma$$

The second Townsend coefficient, γ, is much less than unity and therefore $\log_e \gamma$ is negative. In a typical case about one bombarding positive ion in a hundred will give rise to an electron from the cathode; thus γ is normally of the order of 0·01.

In the above treatment η was assumed to be constant. However, in the vicinity of the cathode the emitted electrons will have a very small velocity and will not be capable of producing ionisation until they have been accelerated. The coefficient η will, therefore, be zero at the cathode. The electrons will have to fall through a potential approximately equal to the ionisation potential, V_i, of the gas before they can produce ions. If one assumes that no ionisation occurs until the electron has moved through this potential difference, one obtains the following modified form of equation 1.1:

$$V_s - V_i \simeq \frac{1}{\eta} \log_e \frac{1}{\gamma} \tag{1.2}$$

Gases such as water vapour, oxygen and ammonia will absorb electrons to form negative ions. Such ions are much heavier than electrons and will not therefore give rise to gas amplification. Thus the presence of such gases lowers the effective value of η. It is normally necessary to exclude gases which will form negative ions from discharge tubes.

The second Townsend coefficient, γ, is not very dependent on the gas pressure or on the field strength, although at very low field strengths the electrons emitted from the cathode may be scattered back to it by gas atoms. It is often assumed that γ is constant for a given cathode material in a specified gas mixture. This approximation is to some extent justified, since γ is normally found in equations as $\log_e \gamma$ and the latter changes fairly slowly with γ. However, γ increases as the work function of the cathode is reduced.

If one assumes that γ is constant for a specified cathode material and gas filling, equation 1.1 shows that V_s is approximately proportional to $1/\eta$. However, the coefficient η depends on the gas and on the field strength. It increases quite rapidly with current density when the space charge is being formed. This rise in η results in the voltage across the tube becoming smaller. If the operating point moves into the abnormal glow region, η decreases with increasing space charge density.

If the current density in a normal glow discharge is below the optimum value for ionisation (i.e. for η to be a maximum), any local increase in the current density will result in more efficient

ionisation at this point and, therefore, a concentration of the current in the region. Thus the discharge will always tend to take up an area of the cathode which results in the value of η being at a maximum.

The maintaining voltage, V_m, is approximately equal to the cathode fall of potential. It is given by the following equation which may be compared with equation 1.2

$$V_m - V_i = \frac{1}{\eta_{\max}} \log_e \frac{1}{\gamma} \qquad (1.3)$$

$\eta_{\max}$ is the maximum value of η for any field strength using a specified gas mixture. Once breakdown has occurred and the space charge has formed in the normal glow region, the value of η becomes equal to $\eta_{\max}$.

Penning mixtures have a high value of η. In the case of gases where ionisation occurs mainly by the collision of metastable atoms with gas molecules, the metastable energy level, V_*, should replace the quantity V_i in the equations.

Electron emission from the cathode is not only attributable to positive ion bombardment, but photoemission may also occur when photons from the discharge strike the cathode. Photoemission plays a relatively minor role when the discharge is in the normal glow region of the characteristic, but is important at the time breakdown is taking place. Photons emitted from the discharge reach the cathode almost instantaneously and, therefore, the current build up by the photoemission process is more rapid than that by processes involving positive ion bombardment.

SERIES RESISTOR

Tubes operating in the normal glow region of the characteristic are invariably used in a circuit employing a current limiting device in series with the tube. If this limiting device, which is normally a resistor, is omitted, the current passing through the tube after breakdown increases until the tube is damaged. When the glow discharge has been initiated in the tube shown in the circuit of Fig. 1.4, the voltage across the tube will be the maintaining voltage, V_m, and therefore the potential across the anode resistor will be $(V_b - V_m)$. Thus the current flowing through the resistor is given by the equation

$$I_k = \frac{V_b - V_m}{R} \qquad (1.4)$$

It should be noted that a small percentage change in the value of V_b can result in a very much larger percentage change in the value of $(V_b - V_m)$ and hence in the value of the current passing through the tube. Care must therefore be taken to ensure that I_k remains within the recommended limits as V_b varies within stated limits. The conditions become easier to satisfy if V_b and R are fairly large.

A maximum permissible value for I_k is stated in the data sheets for each type of cold cathode glow discharge tube. If this value is
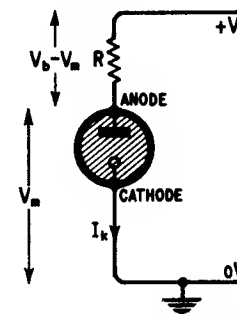

Fig. 1.4. The basic circuit for a glow discharge tube.

exceeded the tube may be damaged. It is important to ensure that this maximum current is not exceeded as the values of V_b and R change within their permissible tolerances. In addition there will be some spread of the maintaining voltage, V_m, from tube to tube. The maximum possible value of I_k will occur when all of these factors combine to produce a high current, that is when V_b is a maximum and when R and V_m are at their minimum values. Hence:

$$I_{k\,(\max)} = \frac{V_{b\,(\max)} - V_{m\,(\min)}}{R_{\min}} \qquad (1.5)$$

A lower limit is also imposed on the cathode current in many types of cold cathode tube. This lower limit is given by the equation:

$$I_{k\,(\min)} = \frac{V_{b\,(\min)} - V_{m\,(\max)}}{R_{\max}} \qquad (1.6)$$

In cold cathode tube circuit design it is especially important to note that a number of factors may combine to affect the current flowing through a tube and the worst possible combined effect of all these factors must be allowed for. The equations 1.5 and 1.6 apply to all tubes operating in the glow discharge region of the characteristic.

CORONA DISCHARGES

A corona discharge occurs from a convex surface of small radius of curvature (such as a needle point or a fine wire) when a high potential is applied between it and another electrode or between it and its surroundings. In such a system the potential gradient near to the surface is very high; indeed, almost the whole of the potential difference between the electrode and it surroundings appears in the vicinity of the convex surface. Under these conditions gas amplification can occur near to the surface giving rise to a partial breakdown and to a self maintaining discharge.

In the dark a corona discharge may be seen as a faint glow or sheath covering the surface of the electrode around which the field strength is high. It may also produce an audible noise. The positive ions formed in the sheath region move relatively slowly towards the cathode, thus forming a space charge which acts like a current limiting resistor.

If the current is allowed to increase, the glowing sheath expands somewhat, but photons from the discharge may form ions at a small distance from the sheath. The ions may give rise to a streamer and if the latter should reach the other electrode, the glowing sheath will disappear and almost all of the current will flow in the streamer.

In most circumstances corona discharges are undesirable; they cause loss of power in transmission lines and may cause trouble in television receiver E.H.T. systems. However, the corona effect (without streamers) is employed in corona stabiliser tubes for the stabilisation of fairly high voltages at currents in the microamp range.

SPUTTER

The ionic bombardment of the cathode of a tube operating in the normal glow region of the characteristic or at a higher current is sufficient to remove some atoms of the cathode material; these atoms are deposited on neighbouring surfaces. This phenomenon, which is known as sputtering, takes place to a much greater extent as the current increases. In general, sputtering occurs to a much smaller extent in tubes which are filled with gases of low atomic weight. Small atoms tend to penetrate into the cathode themselves rather than to liberate atoms of the cathode material. Heavy metal cathodes undergo sputtering more easily than light metals. Sputtering is reduced at high gas pressures, since many of the sputtered atoms are reflected back to the cathode surface by gas molecules.

Sputtering can be employed for the deposition of metal films on surfaces, but in electronic tubes it is often a nuisance. The sputtered metal may be deposited on electrodes near to the cathode and may cause short circuits. In addition it may trap some gas and thus change the characteristics of the tube by reducing the gas pressure in it. The maximum permissible cathode current of a cold cathode tube is often determined by a consideration of the effect which sputtering has on the life of the tube. If an electrode of a cold cathode tube other than the proper cathode is accidentally used as a cathode, heavy sputtering may occur and this will probably destroy the tube.

Nevertheless the phenomenon of sputtering is very useful in the manufacture of certain cold cathode tubes which have pure metal cathodes. Moderately heavy sputtering is deliberately allowed to occur at the cathodes of such tubes during their manufacture in order to leave an extremely pure cathode surface and to remove contaminating gases. Any impurity atoms of gas are trapped beneath the sputtered material on the walls of the tube much more efficiently than atoms of the inert filling gas. This process enables tubes with very close tolerances to be manufactured. It is only the condition of the cathode surface which is so vital to the tube performance, the condition of the other surfaces having a very minor effect.

STATISTICAL DELAY

No current will flow through a gas filled tube until at least one ion has been formed in the gas. A limited number of ions are formed in any gas intermittently by the action of cosmic rays and by the radiation from stray radioactive atoms. These natural sources of ionising radiation cause radiation detectors to register a low 'background' count even when no radioactive materials are intentionally placed in the vicinity of the detector. It is interesting to note that the amount of energy reaching the Earth in the form of cosmic rays is not very different from that reaching the earth in the form of light from stars other than the Sun.

If no way of producing ions is incorporated into a tube, a discharge will not generally occur immediately a potential exceeding the striking potential is applied to the tube. No current will pass through the tube until at least one electron is formed by natural radiation in such a position that it results in gas amplification taking place. Such electrons are formed at random times. Thus one can only state that there will be a certain average delay (known as the

statistical delay) between the time of the application of a specified potential exceeding the striking voltage and the instant at which gas amplification commences. This time is the interval between the application of the potential and the appearance of the electron which initiates the discharge. Not every electron entering the gas will initiate breakdown.

The probability that a single electron will initiate a discharge increases with the over-voltage applied to the tube. The over-voltage is the amount by which the applied potential exceeds the striking voltage. Thus the statistical delay is, on an average, reduced by the use of higher applied potentials. An over-voltage of not less than 40 per cent of the striking voltage should be employed if the statistical delay time is to be minimised.

PRIMING

In many types of tube some method of introducing electrons into the gas is employed in order to reduce the statistical delay time. This process is known as 'priming'.

One method of priming involves the incorporation of a small amount of a radioactive material into the tube. Tritium (hydrogen of atomic weight 3) may be added to the gas filling of the tube; this isotope has a half life of 12·3 years. Alternatively krypton-85, a gas of half life 10·5 years, may be used or a small metal plate on which a little nickel-63 has been deposited may be fixed in the tube near to the cathode. These radioisotopes emit beta particles (i.e. electrons) of moderate energy; the particles can initiate a discharge in the tube. The beta particles cannot penetrate through the glass of the tube, but even if the glass is broken, the amount of the radio-isotope present is not great enough for it to be dangerous. However, the use of radioisotopes complicates the production of such tubes.

The use of a radioisotope does not eliminate the statistical delay, but merely reduces it, since radioisotopes emit their radiation at random times. It is not usually possible to incorporate enough radioactive material in a tube to achieve very short statistical delay times, but radioactive priming is widely used in tubes in which a current is always passing when the equipment is operating (e.g. voltage stabiliser tubes); the function of the priming is merely to ensure that the initial breakdown occurs fairly quickly.

Other methods of priming are normally used in tubes in which the statistical delay must be very small. An auxiliary or priming discharge of a few microamps between two electrodes is often used for this purpose; some of the ions formed in the priming discharge

diffuse into all parts of the tube and can initiate conduction. The priming discharge often flows between the main anode and a separate priming cathode (sometimes called the 'keep alive cathode') or between the main cathode and a separate priming anode (or 'keep alive anode'). However, in some tubes the priming discharge flows between two priming electrodes which are separate from the remaining electrodes.

Photoelectric priming is used in tubes employing cathodes of low work function. A large number of electrons can be obtained at moderate values of ambient light intensity.

An excessive amount of priming must be avoided or the striking voltage of the tube will be lowered until it is little greater than the maintaining voltage. Excessive priming will result in the build up of an appreciable space charge and the resulting increase in the ionisation coefficient reduces the striking voltage.

In addition to the statistical delay, there is a formative delay or discharge build up time. This is the time that elapses between the instant at which the electron which initiates the discharge enters the gas and the time at which the operating point reaches a specified current. Many ionisation cycles must take place before the space charge is fully built up. The formative time depends on the over-voltage, but is often a fraction of a millisecond. The total time between the application of a potential exceeding the striking voltage and the formation of a glow discharge may be referred to as the ionisation time.

In the case of a specified circuit using a certain tube, the formative delay time is constant, whereas the statistical delay time, t_s, varies since electrons enter the gas at random times and not every electron can initiate breakdown. However, the mean statistical delay time, $\bar{t}_s$, is constant for a given tube used in a specified circuit.

If one considers only the statistical delay, the probability that a tube will fail to strike when a rectangular positive going pulse of duration t is applied to the anode is $e^{-t/\bar{t}_s}$. Thus if the failure rate must not exceed 1 in 10^x,

$$\frac{1}{10^x} = e^{-t/\bar{t}_s}$$

$$e^{t/\bar{t}_s} = 10^x$$

$$t = (\log_e 10^x)\bar{t}_s$$

The formative time, t_f, must be added in order to calculate the total pulse time, t'.

$$t' = (\log_e 10^x)\bar{t}_s + t_f \tag{1.7}$$

If a failure rate of 1 in 10^4 is tolerable, equation 1.7 shows that

$$t' > 6\cdot9 t_s + t_f,$$

whilst for failure rates of 1 in 10^6 and 1 in 10^9,

$$t' = 13\cdot8 t_s + t_f$$

and

$$t' = 20\cdot7 t_s + t_f$$

respectively.

DEIONISATION TIME

When a current is flowing through a gas discharge tube operating in the normal glow region, many ions will be present. If the applied potential suddenly becomes zero or merely falls below the maintaining voltage of the tube, the highly mobile electrons pass out of the gas very quickly, but the space charge of positive ions takes longer to disperse. Therefore, if the potential across the tube is subsequently increased to a value between the maintaining and striking voltages, the discharge may be re-formed owing to the presence of the residual space charge.

The deionisation time of the tube may be defined as the minimum time interval between the removal of the applied potential and the application of a specified potential between the maintaining and striking voltages for a discharge not to be reformed. It depends on the current flowing before the applied voltage is reduced below the maintaining voltage, since the large number of ions formed at high currents take longer to disperse. The deionisation time also depends on the re-applied voltage. Deionisation times of rather less than a millisecond are fairly typical.

The smallest values of deionisation time are obtained when the applied potential does not fall to zero, but rather to a value between about one third and two thirds of the maintaining voltage. The potential applied to the tube then assists in the removal of ions from the gas by electrostatic attraction.

Metastable atoms with energy levels exceeding the work function of the cathode can cause electrons to be emitted from the cathode when they strike it. Metastable atoms are electrically neutral and, therefore, cannot be removed by an applied field; they impose a minimum limit on the deionisation times of some tubes. Metastable atoms of low energy are generally longer lived than those of higher energy. The use of a cathode of fairly high work function prevents the relatively long lived metastable atoms of low energy from increasing the deionisation time.

Tubes of short deionisation time have been designed using hydrogen in the gas filling. When a hydrogen molecule collides

with a metastable atom, the energy of the latter is used to dissociate the hydrogen molecule. Hydrogen cannot be used with cathodes which have a work function of less than $4\cdot2$ eV, this being the dissociation energy of the hydrogen molecule.

The ionisation and deionisation times of gas filled tubes limit the maximum speed of operation of circuits in which they are employed. Most gas discharges can be switched on and off in about a millisecond, but in special tubes this time can be reduced to some microseconds. Similar delays occur in the case of counting tubes in which the discharge moves from one electrode to another electrode.

TYPES OF CATHODE

Gas filled cold cathode tubes for use in the normal glow region usually contain either a cathode coated with a material of low work function or a pure metal cathode made of molybdenum or nickel.

Tubes employing coated cathodes generally have lower striking and maintaining voltages than those employing pure metal cathodes owing to the lower value of the work function of the cathode material. The ambient room lighting will cause an appreciable amount of photoemission to occur from cathodes of low work function and this provides the electrons required for prompt striking. In direct bright sunlight coated cathodes emit so many electrons that the striking voltages of the tubes employing them can be lowered almost to the maintaining voltage. Tubes employing such cathodes should not be operated either in bright sunlight or in darkness. A minimum level of illumination is often recommended in the data sheets for such tubes; this is typically 2 ft–candles (20 lux). However, some tubes employing coated cathodes contain a radioactive priming agent so that they can be used inside a dark instrument case.

Photoemission does not occur from pure metal cathodes. Owing to the higher work function of these cathodes, ultra-violet photons are required to produce photoemission, but ultra-violet light cannot pass through the envelope of the tube. If prompt striking is required, tubes with pure metal cathodes must, therefore, employ some method of priming. An auxiliary discharge is often used.

Coated cathodes are damaged if appreciable sputtering occurs. A limited amount of sputtering always occurs during the operation of the tube, however, and therefore the life of tubes employing coated cathodes is generally shorter than those employing pure metal cathodes.

SUGGESTIONS FOR FURTHER READING

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2
Gas Discharge Lamps and Diodes

Miniature neon diodes which operate in the normal glow region of the characteristic are useful both as circuit elements and as miniature indicator lamps. They glow with an orange-red light which is emitted mainly from the negative glow region surrounding the cathode.

Various special types of gas filled diode are available. Special types of indicator tube are described in Chapter 7, tubes for detecting nuclear radiation are described in Chapter 8, whilst voltage stabiliser diodes are described in Chapter 5. Although the miniature neon diodes being described in this chapter can be used for voltage stabilisation at low currents, their performance is not normally so good as that of tubes designed especially for this application.

Miniature neon filled diodes are one of the most commonly used types of cold cathode tube. They are extremely reliable, have a low current consumption and are the cheapest tube of any type which is available. They consist of two electrodes in the form of wires or small plates sealed into a miniature glass envelope about 1 cm in length. The design is normally kept as simple as possible so that the price is kept low. The electrode structure is often symmetrical, in which case the characteristics are independent of the polarity of the applied voltage; such tubes may also be used with supplies of alternating polarity. They may, for example, be used to indicate when the heating element of an electric iron supplied from the mains is operating.

The striking voltage of most miniature neon diodes is about 80 V and the maintaining voltage about 60 V, but these values vary somewhat from type to type. In particular the so called 'difference diodes' have striking voltages of about 160 V, but their maintaining voltages are little higher than that of most other miniature neons.

The large difference between the striking and maintaining voltages of difference diodes simplifies the design of some circuits, allows larger output pulses to be obtained and often increases circuit reliability.

The maximum permissible current rating of many small types of neon diode is 0·5 mA, but some types can pass considerably larger currents. The series resistor should be chosen so that the maximum permissible current is never exceeded (see equation 1.5). If the value of the series resistor is too high, the amount of light emitted will be small.

NEON LAMPS

Neon diode lamps are available in a number of forms. The small types are merely connected in series with a suitable current limiting resistor across two points of a circuit; the neon tube strikes when the potential between the two points exceeds the striking voltage of the tube. The potential across the tube then falls to the maintaining voltage. Some slightly larger tubes have the current limiting resistor built into the base of the tube. One of these larger types is the 'beehive' neon lamp which normally has a bayonet base for fitting into a standard 240 V a.c. mains lamp socket; the name is derived from the spiral structure of one of the electrodes which gives the latter the shape of one type of beehive. This lamp is similar in size to a domestic electric lamp.

The cathode of a neon tube is partly covered by the glow, but in tubes operating from an a.c. supply both electrodes appear to be covered by the glow, although they are actually each covered in turn during a cycle of the a.c. supply. The amount of light emitted is approximately proportional to the current flowing; it is not so dependent on the supply voltage as the tungsten filament lamp.

Although the electrical characteristics of a neon lamp remain almost constant throughout its life, the material sputtered onto the tube envelope will gradually cause blackening of the latter and this results in a reduction of the light output. It is an important advantage of the neon lamp that the termination of its life does not normally occur by total breakdown (as in the case of a tungsten filament lamp), but rather by a gradual reduction in the amount of light emitted. This enables a neon lamp to be replaced well before total failure occurs, for example, when all of the cathode has been sputtered away. The sensitivity of the human eye is approximately logarithmic and, therefore, an old neon lamp which is emitting only about ten per cent of the amount of light emitted by a new tube will appear only a little less bright. In a correctly designed circuit this

stage is not usually reached until the tube has been passing the maximum rated current for perhaps 20,000 to 100,000 hours.

If suitable fluorescent materials are placed on the inside of the envelope of a neon tube, they will be excited by the ultra-violet radiation from the discharge. A wide variety of colours can thus be obtained. A little mercury vapour is included in the gas filling of such lamps to increase the amount of ultra-violet radiation produced in the discharge.

In the long neon tubes used for advertising and display purposes, most of the light is emitted from the positive column. The striking voltage of such tubes may be about 10,000 V, but the maintaining voltage is considerably less than this. If a series resistor were used as a current limiting device, a large amount of power would be dissipated in this resistor. A transformer with a high leakage inductance is normally used to feed the tube. When the neon tube passes a current, the secondary voltage of this type of transformer falls considerably. Long tubes produce light more efficiently than short ones, since a greater fraction of the applied potential appears across the positive column; however, long tubes require a greater potential than short ones.

If a neon lamp is placed in series with its current limiting resistor across a fuse, the lamp will glow when the fuse breaks (assuming that the circuit employs potentials in excess of the striking voltage of the tube). Thus a visible indication is given as to which fuse requires replacement. One type of fuse contains a gas so that the fuse itself glows when it requires replacement.

Neon lamps may be employed as voltage monitors in H.T. supplies. For example, a neon may be connected between the anode of a thermionic valve and earth. If the cathode or heater circuit of this valve becomes open circuited, the anode current will fall to zero and the anode voltage will rise. This will cause the neon to glow and provide a visual indication as to which of the valve circuits is faulty. Similarly if the valve anode current falls below a certain preset figure owing to valve ageing, the neon indicator tube will glow.

APPLICATIONS OF NEON DIODES AS CIRCUIT ELEMENTS

RELAXATION OSCILLATOR

The simple circuit of Fig. 2.1 (a) can be used to produce relaxation oscillations at a frequency determined mainly by the value of the
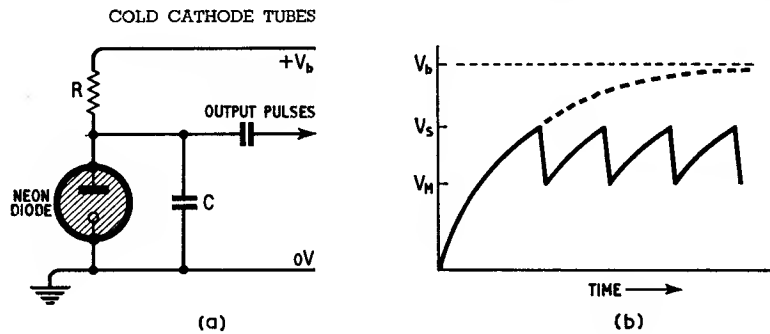
(a)   (b)

Fig. 2.1. A relaxation oscillator; the output waveform is shown at (b).

resistor R and the capacitor C. Such oscillators can produce pulses for the operation of other cold cathode tube circuits. They may also be used in electronic organs, since the output waveform is very rich in harmonics.

When the supply voltage is first applied to the circuit, a current flows through the resistor R to charge the capacitor C. The neon diode does not conduct until the voltage across C exceeds the striking voltage of the tube. The capacitor then discharges through the neon quite rapidly until the potential across the tube is inadequate to maintain the discharge. The capacitor then charges again until striking re-occurs. The rise of the output potential from V_m to V_s followed by a rapid fall back to V_m is shown in Fig. 2.1 (b). The output is known as a saw tooth waveform for obvious reasons. Difference diodes are especially suitable for use in relaxation oscillators of this type, since they produce larger output pulses than the normal miniature diodes.

Oscillation will not occur unless the value of R is fairly large (typically greater than 200 kΩ), whilst fairly large values of C render oscillations more probable. The maximum frequency of oscillation is limited by ionisation and deionisation times, being typically a few kilocycles.

The time for the capacitor C to charge exponentially through R from the supply voltage, V_b, to any voltage V is given by

$$RC \log_e \frac{V_b}{(V_b - V)}$$

The time, t, for the capacitor to charge from V_m to V_s from the supply potential V_b is equal to the time to charge from zero voltage to V_s minus the time to charge from zero voltage to V_m. Therefore:

$$t = RC \log_e \frac{V_b}{(V_b - V_s)} - RC \log_e \frac{V_b}{(V_b - V_m)}$$

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Hence

$$t = RC \log_e \left\{ \frac{V_b - V_m}{V_b - V_s} \right\}$$

This is the charging time. The time taken for the potential across the capacitor to fall from V_s to V_m is usually much smaller than t. Thus the frequency of oscillation of the circuit, f, is given by the approximate equation

$$f = \frac{1}{RC \log_e \left\{ \frac{V_b - V_m}{V_b - V_s} \right\}} = \frac{1}{2 \cdot 303 RC \log_{10} \left\{ \frac{V_b - V_m}{V_b - V_s} \right\}} \quad (2.1)$$

In practice the frequency will be slightly less than the value given by this equation partly because the discharging time is not quite zero and partly because the capacitor discharges to a potential
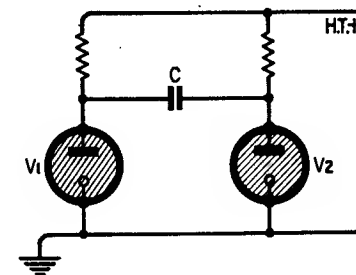
Fig. 2.2. An oscillator using two neon diodes.

slightly less than V_m. The frequency stability is not good, since the frequency is dependent on the supply voltage, V_b, and on the tube characteristics.

If the value of C is not relatively small, it will be necessary to place a resistor between the tube and this capacitor in order to limit the current to a value which will not damage the tube. This resistor may be placed between the cathode of the tube and earth, in which case the output may be taken from across the resistor. Alternatively, the current limiting resistor may be placed between the lower plate of the capacitor and earth, in which case pulses of the opposite polarity may be taken from across it.

The circuit of Fig. 2.2 employs two neon tubes which conduct alternately. When the H.T. supply voltage is first applied, one of the tubes, say V_1, conducts and its anode voltage falls from the striking voltage to the maintaining voltage. This negative pulse is applied to the anode of V_2 via the capacitor and prevents the latter

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tube from striking. As the capacitor charges, however, the anode potential of $V2$ rises until this tube strikes. The fall of anode potential of $V2$ is applied to the anode of $V1$ via the coupling capacitor and $V1$ is thus extinguished. The tubes continue to conduct alternately. The frequency is determined by the values of the capacitor and resistors used and by the tube characteristics.

TIMING CIRCUITS

The type of circuit shown in Fig. 2.3 may be used for producing a pulse at a predetermined time interval after the application of the H.T. supply voltage.

When the power supply is first connected, the capacitor C commences to charge through the resistors R and R'. After a time the striking voltage of the tube is reached and C discharges through it.
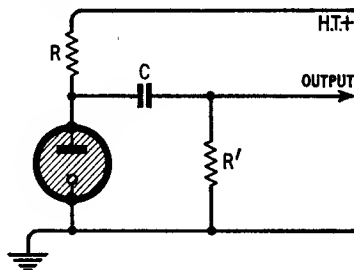
Fig. 2.3. A neon diode timer.

A negative going pulse is thus produced across R'. If a positive going pulse is required, this resistor may be placed in the tube cathode circuit instead of in the position shown.

The output pulse obtained after the preset interval may be used to operate other equipment. The interval may be altered by changing the value of C or R.

SPEECH SWITCHING

If the voltage applied to the anode circuit of a conducting neon diode is modulated at an audio frequency, the modulations will be present in the diode anode current; hence the audio signal can be taken via a capacitor from across the tube cathode resistor. However, if no H.T. potential is applied to the circuit or if the H.T. potential is not great enough to cause the tube to strike, no audio

output will be obtained, since the tube will act as an infinite resistance. Such circuits can be used for routing speech signals to a desired point in a telephone network.

A normal cold cathode diode will attenuate audio frequencies and introduce additional noise. Special tubes known as 'speech tubes' have been developed for this application to minimise these undesirable effects.

COUNTING CIRCUITS

Neon diodes can be used for counting electrical pulses, although other types of component are now often preferred for this purpose. One type of neon diode counting circuit is shown in Fig. 2.4.

When the H.T. potential is first applied to the circuit, one of the tubes will conduct as soon as the potential across it reaches the striking potential of the tube. The tubes will not all have precisely the same striking voltage and in addition the statistical delay will vary somewhat from tube to tube. One tube will therefore strike before the others. Let us assume that $V0$ strikes first. The common anode potential will then be equal to the maintaining voltage of $V0$ plus the voltage drop across the cathode resistor R_0. If this resistor is fairly small, the common anode voltage will not be great enough to cause any other tube to strike. Thus the one tube $V0$ remains glowing and this is taken to indicate a count of zero. The capacitor C_0 is charged to a voltage equal to that across R_0.
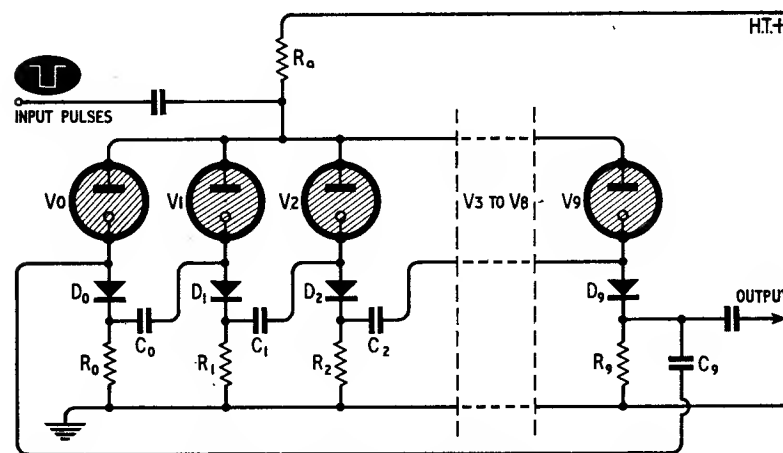
Fig. 2.4. A neon diode counting circuit ($V3$ to $V8$ inclusive have been omitted for simplicity).

When a negative going input pulse is applied to the anodes of the tubes, the common anode voltage is reduced below the maintaining voltage and Vo is extinguished. C_0 is prevented from discharging rapidly because it biases the semiconductor diode D_1 in the reverse (or high resistance) direction. Thus the cathode of $V1$ receives a negative potential from C_0 when Vo is extinguished. The potential across $V1$ is therefore greater than that across any of the other neon diodes. Thus $V1$ will strike preferentially as the common anode voltage rises at the end of the input pulse. No other tube will strike, since the potential drop across R_a resulting from the flow of current to $V1$ ensures that the common anode potential is less than the striking voltage of the tubes. The glow in $V1$ shows that one pulse has been counted.

A second pulse will cause the glow to move to $V2$ and so on. For simplicity the circuits of $V3$ to $V8$ have been omitted from Fig. 2.4, but they are similar to the circuits of the other tubes shown. When $V9$ is glowing and a further input pulse is received, the glow will be transferred to Vo and an output pulse will be produced. One output pulse is thus produced for each ten input pulses applied to the circuit. The output pulses may be counted by another similar circuit which indicates the number of tens and the output pulses from this latter circuit may be counted by a third circuit which indicates the number of hundreds, etc.

A circuit such as that of Fig. 2.4 is known as a decade counting circuit, since it counts in a scale of ten in the same way that we use the scale of ten in normal counting. The circuit is also a 'ring counter', since the state of conduction steps around the ring of ten neon diodes. Decade counting circuits are 'divide by ten' circuits, since they provide one output pulse for each ten pulses applied to the input. Any reasonable number of tubes may be employed in the ring to divide the incoming pulse frequency by any desired factor.

Counting circuits may be used for counting the pulses from a Geiger counter tube, for counting the number of articles coming off a production line or for many other applications in industry and in research.

D.C. COUPLING

Neon diodes may be used to couple the anode of an amplifier valve to the grid of the next stage. They have the advantage over a capacitor that they present a lower impedance to very low frequencies and can be used at zero frequency.

DATA LOGGING

Neon diodes may be used to provide an indication that a pulse has reached the diode circuit. The H.T. voltage has a value between the maintaining and striking voltages of the tube. If a suitable positive going pulse is fed via a capacitor to the anode of the tube, the latter will strike. The glow from the tube will indicate that the pulse has arrived. Alternatively the series resistor may be placed in the cathode circuit instead of in the anode circuit, in which case a negative going pulse applied to the cathode via a capacitor will cause the tube to strike.

An array of miniature neon diodes may be included in the indicator panel of many different types of equipment. As each operation is carried out by the equipment, a pulse is fed to the appropriate neon. Each tube glows in turn until the sequence of operations is complete, when the H.T. supply is momentarily interrupted to extinguish all of the tubes.

GLOW MODULATOR TUBES

Glow modulator tubes have been specially developed to provide a light output of a high intensity which is dependent on the current passing through the tube. Such tubes are mainly produced for scanning and facsimile equipment used for picture transmission. The original picture is scanned at the transmitter using a photosensitive device and the resulting signal is used to modulate a radio carrier wave. At the receiver the carrier wave is demodulated and the resulting signal is used to control the current passing through a glow modulator tube. The light output from the tube is projected onto a sheet of photographic material by a scanning device so that a reproduction of the original is obtained on development.

Glow modulator tubes employ a hollow cathode of about 1 mm diameter. The illuminated area of the cathode is made as small as possible to facilitate projection by an optical system. The cathode, which is formed by drilling a hole in the end of a metal rod, is mounted inside a ceramic tube open at one end so that no discharge can take place to the outside of the electrode. The anode is mounted at the open end of the ceramic tube and contains a hole through which the light beam escapes. The gas filling normally contains argon.

The striking voltage of glow modulator tubes is typically 200 V and the maintaining voltage about 150 V. The continuous current rating may be of the order of 5 to 30 mA and the uppermost modulation frequency as high as 1 Mc/s. The life of most glow

modulator tubes is limited to about 200 hours, mainly because sputtering results in a reduction of the gas pressure and blackening of the inside of the tube.

TR CELLS

TR cells (transmit/receive switches) are used in radar systems to enable a single aerial to be used for both transmission and reception. These cells, which are also known as duplexer valves, effectively consist of a gas filled capacitor. When the transmitter pulse is fed to the aerial, a gas discharge takes place in the TR cell forming a short circuit across the transmission line. This results in the signal being passed to the aerial and the receiver is protected from over-loading.

A very short time after the pulse has been transmitted, a reflected pulse may be received at the aerial. This echo signal is too weak to initiate a discharge and it therefore passes to the receiver. More complicated systems are also frequently used.

SUGGESTIONS FOR EXPERIMENTS WITH NEON DIODES

EXPERIMENT 1. *Neon diode characteristics*

Construct the circuit of Fig. 2.5 using a Hivac NT2 neon diode or a similar tube. The voltmeter, V, should be a valve voltmeter or a high impedance transistor voltmeter. The maximum value of the H.T. supply voltage should be about 250 V; it must be variable.

Increase the H.T. voltage until the tube strikes. Reduce this voltage until the tube is extinguished and then increase it again
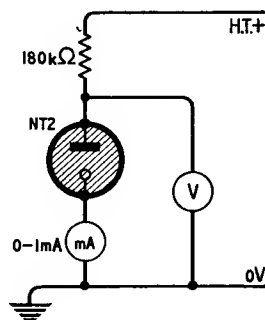
Fig. 2.5. *A circuit for the measurement of neon diode characteristics.*

until striking re-occurs. Repeat this a few times, noting how the current varies. Note the value of the voltage applied to the tube immediately *before* striking occurs as the applied potential is raised *very slowly*; this is the striking voltage. Note the voltage across the tube when it is conducting; that is, note the maintaining voltage. Ascertain whether there is an appreciable variation in the maintaining voltage as the current passing through the tube is varied by a change in the H.T. potential. Note also how the fraction of the cathode surface covered by the glow varies as the cathode current is changed.

Why is it necessary to increase the applied anode voltage very slowly when the striking voltage is being found?

EXPERIMENT 2. *Ionisation time*

A pulse generator providing square waves of at least about 80 V in amplitude is required for this experiment. The circuit used is
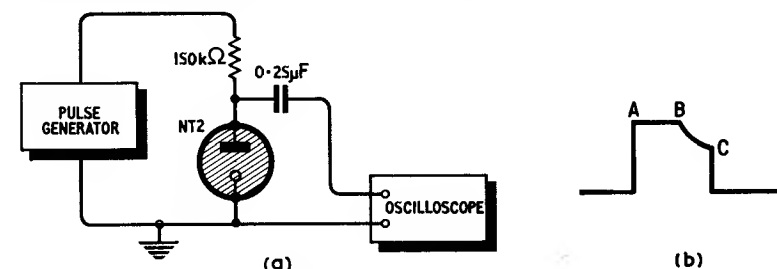
Fig. 2.6. *Measurement of ionisation time.*

shown in Fig. 2.6(a), but if pulses with an amplitude greater than about 175 V are to be used, the value of the anode resistor should be increased so that there is no danger of the maximum rated current being exceeded (1 mA for the NT2 tube).

If the pulses are very short in duration, the ionisation time of the tube will exceed the pulse length and no current will pass through the tube. In this case the oscilloscope will show a pattern corresponding to the rectangular pulses produced by the generator. As the duration of the pulses is increased, however, the diode will conduct at a time equal to the ionisation time after the start of each pulse. The general appearance of the oscilloscope trace will then be as in Fig. 2.6(b). The anode voltage commences to fall at B and reaches the maintaining voltage before the pulse terminates at C. The ionisation time may be found by estimating the time

between A and B from the oscilloscope pattern. Alternatively the pulse duration may be reduced until the point B coincides with the end of the pulse; the ionisation time is then equal to the pulse duration (which may be read from the generator setting).

Various values of the pulse voltage may be employed and a graph of the ionisation time can then be plotted against pulse voltage.

EXPERIMENT 3. *Relaxation oscillator*

Construct the relaxation oscillator circuit shown in Fig. 2.7 using close tolerance components for R and C. The value of R may be
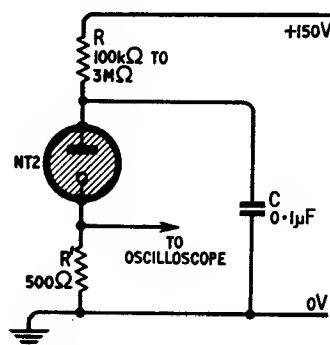
Fig. 2.7. A relaxation oscillator.

1 MΩ initially. Examine the waveform of the potential across R′ using an oscilloscope. Examine also the waveform across the capacitor C and estimate the difference between the striking and maintaining voltages of the tube. Compare this difference with that obtained in experiment 1 using the same tube. (At high frequencies the ions formed in one discharge may reduce the striking voltage for the succeeding discharge.)

Use the oscilloscope to find the frequency of oscillation. Find how the frequency varies with the value of R. This resistor should not be made less than about 100 kΩ or an excessive current will flow and damage the tube. Plot a graph of $\log_{10}$ (frequency) against $\log_{10} R$.

Determine the frequency of oscillation using smaller values of the capacitor C than that in Fig. 2.7. What happens when C is zero or very small? Plot a graph of $\log_{10}$ (frequency) against $\log_{10} C$.

From the slopes of the graphs deduce a relationship between R, C and the frequency of oscillation of the circuit. As a check

plot R against the reciprocal of the frequency and then, on the same sheet of paper, C against the reciprocal of the frequency. Is it possible to estimate the stray anode to cathode capacity from the graph?

Plot a graph of frequency of oscillation against the H.T. voltage with R = 1 MΩ and C = 0·05 μF over an H.T. voltage range of 150 to 500 V.

Choose a number of your results to check the accuracy of equation 2.1 over a wide frequency range.

SUGGESTIONS FOR FURTHER READING

NEON DIODES
'A new family of gas filled diodes', *Electron. Appl. Bull.*, 23, 3, 89 (1962/3).
D. W. WRIGHT, 'Primed cold cathode diodes', *I.E.R.E. Symp.*, Cambridge (1964).

GLOW MODULATOR TUBES
D. REES, 'The design and operation of glow modulator tubes', *I.E.R.E. Symp.*, Cambridge (1964).

3
Trigger Tubes

Trigger tubes are very similar to neon diodes, but contain at least one additional electrode. The simplest type of trigger tube contains three electrodes, namely the main anode, the cathode and the trigger or starter electrode. The latter normally acts as an additional anode. The tube may be considered as a double diode with a common cathode in which ionic coupling is employed between the trigger to cathode and main anode to cathode gaps.

A trigger tube is often operated from an H.T. supply potential greater than the maintaining voltage but less than the striking voltage of the main anode to cathode gap. If a suitable positive pulse is applied to the trigger electrode, the trigger to cathode gap will conduct, the discharge taking place in the normal glow region of the characteristic. The ions produced by this discharge are able to initiate conduction in the main anode to cathode gap. If a suitable relay is connected in the anode circuit, a very small current pulse at the trigger electrode will cause the anode circuit to conduct and energise the relay.

The action of the trigger electrode is not reversible in the way that the grid of a thermionic valve can be biased so as to increase or decrease the anode current being passed by the valve. Once a trigger tube has commenced to conduct, the potential of the trigger electrode has no effect on the discharge in the main anode to cathode gap. The main anode current can be reduced to zero only by a reduction of the main anode to cathode voltage below the maintaining voltage of this gap.

Trigger tubes can replace thermionic valves, transistors and thyratrons in many types of application involving switching. Their main advantages are that they consume no heater power, are completely inoperative during stand-by periods (taking no power

whatsoever), have a long life and a high input impedance. They do, however, require a moderately high voltage to initiate conduction and have a limited maximum operating frequency.

CHARACTERISTICS

The gap between the trigger electrode and the cathode is smaller than that between the main anode and the cathode. The trigger to cathode striking voltage is, therefore, normally considerably less than the striking voltage of the main gap. The maintaining voltage of the trigger to cathode gap is also somewhat less than that of the main gap.

The current passed by the trigger electrode of a tube before it is switched to the conducting state is very small indeed. In some circuits this pre-strike trigger current is typically 10^{-9} A so that current gains of 10^7 are common. Special 'electrometer' trigger tubes have been produced which have pre-strike currents of less
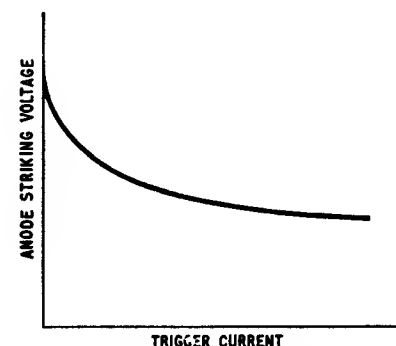
Fig. 3.1. A trigger tube transfer characteristic.

than 10^{-12} A; such tubes can provide current gains of about 10^{10} and power gains of about 10^{12}.

The striking voltage of the main anode to cathode gap is lowered by the flow of trigger current, since a partial space charge is formed. The greater the trigger current, the greater the number of ions formed and the greater the amount by which the striking voltage of the main anode to cathode gap is lowered towards its maintaining voltage. In Fig. 3.1 the discharge in the main gap is initiated at points above the curve. Thus the current which must pass to the trigger electrode to initiate conduction in the main gap will depend on the applied anode voltage. The trigger current required to cause

conduction is known as the transfer current. The smallest values of transfer current are found in tubes employing a Penning mixture at a low pressure.

The maximum anode supply voltage specified in the tube data sheets is the maximum value which permits the trigger electrode to control ignition in all tubes of the type concerned. Larger values of anode voltage may result in the spontaneous striking of the anode to cathode gap. The striking voltage is usually two to three times the maintaining voltage. Trigger tubes are designed to have high values of the main anode striking voltage so that a large change of the anode voltage occurs on ignition. However, tube designers do attempt to obtain a minimum value of the trigger striking voltage.

IGNITION CHARACTERISTICS

In a trigger tube a discharge may be initiated between any two of the three electrodes, the current passing in a direction which is determined by the polarity of the applied voltage. The type of diagram shown in Fig. 3.2 may be used to depict the potentials which must be applied to the tube to initiate conduction. A separate diagram of this type is, of course, required for each type of trigger tube. This curve does not provide any information about the behaviour of a tube which has already commenced to conduct, but only about the conditions necessary for conduction to occur.

If the anode and trigger potentials with respect to the cathode can be represented by a point inside the inner curve, A, no tube of the type number concerned will pass either trigger or anode current. If the operating point is outside the curve marked B, all tubes will strike between two of the electrodes and the ions thus formed may initiate a discharge to the third electrode. Two curves are necessary in order to take account of the tolerances from one tube to another of the same type number. At operating points between the two curves some tubes will pass a current, whereas others of the same type number will remain non-conducting. Curve A represents values of the minimum striking potentials, whilst curve B represents maximum values.

If one starts at the origin and gradually increases the trigger potential whilst leaving the anode potential unaltered at zero, the operating point moves to the right along the axis. At some point between the curves A and B a current flows from the trigger to the cathode. Similarly if one leaves the trigger potential at zero and increases the anode potential, the operating point rises vertically
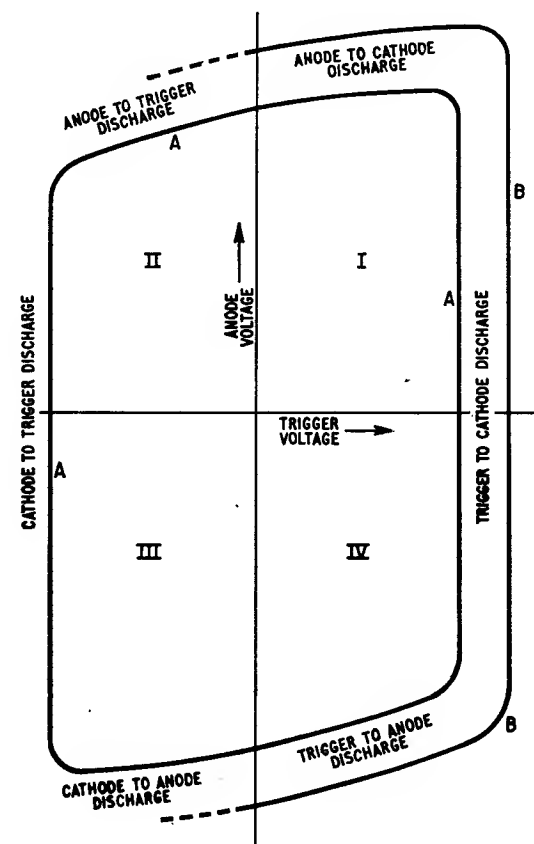
Fig. 3.2. Trigger tube ignition characteristics.

from the origin until at some point between the two curves a current passes from the anode to the cathode.

Almost all trigger tubes are designed for operation in quadrant I of Fig. 3.2 where the cathode potential is never more positive than that of either the trigger or the anode. If the trigger or anode potential is made negative with respect to the cathode, the operating point will move to the left or downwards on the diagram. No damage will be done to the tube provided that no current flows in the reverse direction. This will not occur if the minimum striking voltage is not exceeded, that is, if the curve A is not crossed. The circuit designer is not interested in the outer curve, B, in quadrants where reverse anode or trigger current can flow, since circuits should be designed so that there is no possibility of ignition occurring and

causing reverse currents to flow in any tube of the type number being considered. Thus curve A is a warning line which may be crossed only in quadrant I.

There are, however, a few rather exceptional trigger tubes in which the trigger is designed to operate at a negative potential with respect to the cathode. Such tubes are designed for operation in quadrant II without being damaged in any way. When such tubes are being used, there is no objection to the curves of Fig. 3.2 being crossed in quadrant II.

It can be seen from Fig. 3.2 that the trigger striking voltage is virtually independent of the main anode voltage. This is a very desirable property in any trigger tube.

Trigger tubes should not be mounted very close to any conductor (unless the tube data sheets state that such mounting is permissible), since this may give rise to spurious ignition if the conductor collects an electro-static charge.

TYPES OF TRIGGER TUBE

Trigger tubes employing coated cathodes normally have trigger striking voltages of about 70 to 90 V, whereas those employing pure molybdenum cathodes have trigger striking voltages of about 125 to 160 V. Tubes employing pure metal cathodes have characteristics which are much more stable throughout life and such tubes can be manufactured with close tolerances. However, higher potentials are needed for their operation than in the case of tubes using coated cathodes.

Some trigger tubes contain two trigger electrodes which are electrically equivalent. A discharge from either trigger to the cathode is capable of initiating the main discharge. Such tubes are useful where two independent inputs are required such as in reversible counting circuits.

One type of tube has a shield anode between the main anode and the cathode; this electrode can be used to control the potential gradients between the main anode and the cathode. A potential of about two thirds of the main anode potential is often applied to the shield anode. The inclusion of this electrode raises the striking voltage of the tube, thus enabling higher supply voltages to be employed. The use of a shielded anode tube therefore enables the trigger electrode to control a higher power in the anode circuit load for the same cathode current. Such tubes can also be supplied with power from rectified but unsmoothed a.c. mains. In one type of shielded anode tube the potential required by the shield

is derived from the charge collected by this electrode, no external connection being provided.

Almost all trigger tubes with pure metal cathodes are provided with a priming anode or a priming cathode. In the G1/371K tube an auxiliary discharge occurs between two priming electrodes and the ultra-violet photons thus produced pass through a mica window into the main gap where they create the ions required for priming. This tube employs a special gas mixture and a shield electrode to enable very small ionisation and deionisation times to be obtained.

Tubes which are to be used essentially as power amplifiers (e.g. for relay operation) are designed to pass a much greater anode current than those designed for switching operations.

IONISATION TIMES

The time between the application of a pulse to the trigger electrode and the establishment of a glow discharge in the main anode gap is the sum of a number of delay times. These are:

1. The statistical delay time which occurs between the application of a pulse to the trigger electrode and the entry of the electron which initiates the discharge.
2. The formative delay of the trigger gap; this is the time interval between the instant the electron enters the gap and the establishment of a full trigger to cathode glow discharge.
3. The time required by the ions in the trigger discharge to cause breakdown of the main anode to cathode gap.
4. The formative time of the main gap; that is, the time required for the current in the main gap to rise to the glow discharge condition.

The sum of the last two terms is known as the transition time. If the trigger electrode is situated in the main gap, the third term may be zero.

The total ionisation time is very dependent on the trigger over-voltage (that is, on the amount by which the trigger voltage exceeds the trigger striking potential). Both the statistical and formative delays of the trigger tube fall with increasing trigger over-voltage. The statistical delay of the trigger gap is the only parameter normally affected by the number of priming ions present in the tube; the trigger striking voltage is unaffected by the relatively small number of ions formed by the usual methods of priming.

The probability of a trigger tube failing to strike when a trigger pulse of a specified duration is applied to it may be determined by

equation 1.7. Although this equation does not take into account the transition time, it nevertheless determines the probability of the trigger gap striking. Once ignition has taken place in this gap, striking of the main gap will automatically follow provided that the trigger current is adequate for the anode voltage employed.

The deionisation time of a tube is the time for which the supply voltage must be removed in order that the tube will not restrike on the re-application of a specified potential. It is the time required for the majority of the space charge to disperse. The deionisation time is generally longer than the ionisation time and thus limits the frequency of operation of many trigger tube circuits. The deionisation time increases with the current which has been passing through the tube.

HYSTERESIS

Trigger tubes show thermal hysteresis effects. Trigger hysteresis is the change of the trigger striking voltage which occurs immediately after a tube has been passing a fairly high current for at least several seconds. Similarly anode hysteresis is the reduction in the anode striking voltage after a fairly high current has been passing through the tube.

TRIGGER CIRCUITS

The simplest possible trigger circuit involves the use of a resistor connected to the trigger electrode (Fig. 3.3(a)). In order for the main anode to take the discharge, the trigger resistor, R_T, must pass a current exceeding the transfer current, I_T. Therefore:

$$R_T < \frac{V_T - V_m'}{I_T}$$

where V_T is the voltage used to trigger the tube and V_m' is the trigger to cathode maintaining voltage. The value of R_T is typically some hundreds of thousands of ohms. The applied voltage, V_T, can cause triggering if it exceeds the trigger striking voltage by only a few millivolts, since the pre-strike current flowing through R_T produces only a minute voltage drop.

The circuit of Fig. 3.3(b) can be designed with a much higher input impedance than that of Fig. 3.3(a). When the potential V_T is applied, the capacitor C_T charges through the resistor R_T until the potential across this capacitor reaches the trigger striking voltage
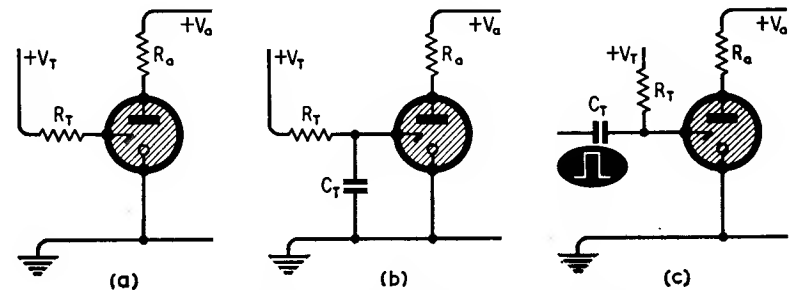
Fig. 3.3. (a) Current triggering; (b) capacitive triggering; (c) pulse plus bias triggering.

of the tube. If the value of C_T is not too small for the particular anode voltage employed, the charge from this capacitor passing through the trigger gap will be adequate to initiate conduction in the main gap; that is, the charge stored in C_T will produce a current great enough to cause transfer. The value of R_T in the circuit of Fig. 3.3(b) may be some hundreds of megohms. In general the capacitor C_T should be chosen to satisfy the following condition:

$$C_T > 2 \left\{ \frac{I_T t}{(V_T - V_m')} \right\}$$

where t is the ionisation time of the trigger tube. The disadvantage of capacitive triggering is that a small delay occurs between the application of the triggering voltage, V_T, and the firing of the tube, since C_T takes time to charge through R_T.

The third method of firing a trigger tube is known as the 'pulse plus bias' technique (Fig. 3.3(c)). The bias V_T applied through the resistor R_T is smaller than the trigger striking voltage. The firing pulse, which is applied through C_T, need be of only a few volts in amplitude if V_T is only a little less than the trigger striking voltage.

EXTINCTION

The discharge in a trigger tube must be extinguished before the tube can be used in a further operation. In some circuits the anode discharge is extinguished by the application of a negative going pulse to the anode or alternatively, if the current limiting resistor is placed in the cathode circuit, by the application of a positive going pulse to the cathode. In either case the pulse must be longer than the deionisation time of the tube. Suitable negative going pulses are obtainable from the anode of another trigger tube which

is in the process of being ignited, whilst positive going pulses may be obtained from the cathode of another trigger tube which is being ignited.

Another method of effecting anode circuit extinction involves the use of a rectified but unsmoothed power supply. Extinction takes place when the instantaneous value of the power supply voltage falls in each alternate half cycle of the mains supply. When this technique is used, it is often possible to supply the circuit with power by rectifying the mains voltage directly without the use of a mains transformer.

A third method of extinction involves the use of a relay in the anode circuit of the trigger tube. When the tube conducts, the relay is energised and a pair of contacts on the relay opens, thus breaking the anode power supply circuit.

If a high value resistor is included in the anode circuit of a trigger tube and a capacitor is connected from the anode to earth, self extinction will occur (as in Fig. 2.1). Oscillation will not take place in the trigger tube anode circuit, however, unless the anode supply voltage exceeds the anode striking voltage of the tube.

Trigger tube data sheets recommend maximum and minimum values of the cathode current in a conducting tube. An excessive current can damage the cathode, whilst a very small current may result in instability. The total series resistance placed in the anode-cathode circuit of the tube should therefore be chosen so as to satisfy the requirements of equations 1.5 and 1.6.

Practical examples of some of these circuit techniques will now be discussed.

SOME APPLICATIONS OF TRIGGER TUBES

RELAY OPERATION

Trigger tubes, which are also known as relay tubes, can be employed to operate a relay from an input which cannot itself supply enough power to operate the relay. The basic circuit for relay operation is shown in Fig. 3.4. When the input voltage exceeds the trigger striking potential of the tube, ignition takes place and the relay closes. It will remain closed until the H.T. supply is interrupted. If, however, it is required that the relay shall close only momentarily, a pair of normally closed contacts on the relay may be used to interrupt the power supply voltage and hence to extinguish the discharge in the tube. The resistor in the anode circuit should have a value which is great enough to protect the trigger tube from

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Fig. 3.4. The basic circuit for the operation of a relay.
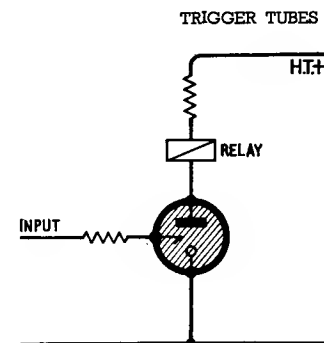
excessive current, but if it is too large the current passing through the relay may not be great enough to operate the latter. The techniques of the circuits of Figs. 3.3(b) and 3.3(c) may also be used for controlling a relay.

PHOTOELECTRIC SWITCH

In the circuit of Fig. 3.5 (designed by Ericsson Telephones Ltd.) a beam of light falling on to a photoconductive cell is used to control the operation of a relay. The trigger tube employed is the Ericsson GPE120T which has a shield anode and a priming anode in addition to the normal main anode. The priming current is limited to a few microamps by the presence of the 10 MΩ resistor. The circuit is fed directly from the 240 V a.c. mains—no mains transformer being required. The discharge in the trigger tube is
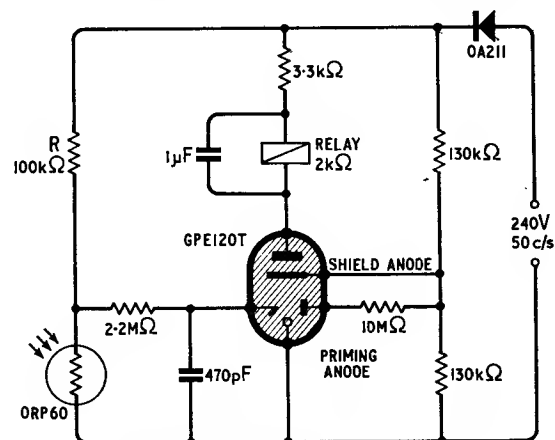
Fig. 3.5. A relay circuit controlled by a beam of light.

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extinguished during each alternate half cycle of the mains supply when the OA211 rectifier does not conduct.

The resistor R and the ORP60 cadmium sulphide photoconductive cell form a potential divider circuit. When light is falling on the cell, its resistance is low and, therefore, the potential applied via the $2 \cdot 2$ MΩ resistor to the trigger electrode is very small. Thus the trigger tube does not conduct. When the light beam is interrupted, however, the resistance of the photoconductive cell increases and, therefore, the potential applied to the trigger electrode is positive during the alternate half cycles of the mains supply when the OA211 diode conducts. Thus the tube is ignited and a current flows through it during alternate half cycles. The capacitor in parallel with the relay stores enough charge during the periods of conduction to ensure that some current passes through the relay when the OA211 is non-conducting. Thus the presence of this capacitor prevents the relay from 'chattering'.

The contacts of the relay may be used to operate any other piece of equipment. If the positions of the photoconductive cell and the resistor R are transposed, the relay will close when light is falling on the cell. Photoelectronic switching circuits have many applications, for example, detecting when the flame of a furnace is extinguished.

LEVEL CONTROL

A circuit developed by the Cerberus Company of Switzerland for controlling the level of a liquid which will conduct to some extent is shown in Fig. 3.6. A transformer is normally employed in such circuits for safety reasons in order to enable the liquid container to be isolated from the mains supply. The trigger tube employed is the Cerberus type GR16 which has an internal shield electrode (shown on the right-hand side of the tube in Fig. 3.6). This tube can operate from a.c. or d.c. power supplies and, therefore, a power supply rectifier is not required.

When the level of the liquid falls below point B, the relay closes and switches on the pump which supplies more liquid to the container. The pump continues to operate until the liquid level rises to the point C. The difference in the levels of the points B and C ensures that the pump is not switched on and off too frequently.

When the liquid level is high, the $1 \cdot 2$ MΩ resistor in the trigger circuit forms a potential divider in conjunction with the resistance of the liquid between the points A and B. The resistance of the liquid should not exceed 100,000 Ω between the point A and each
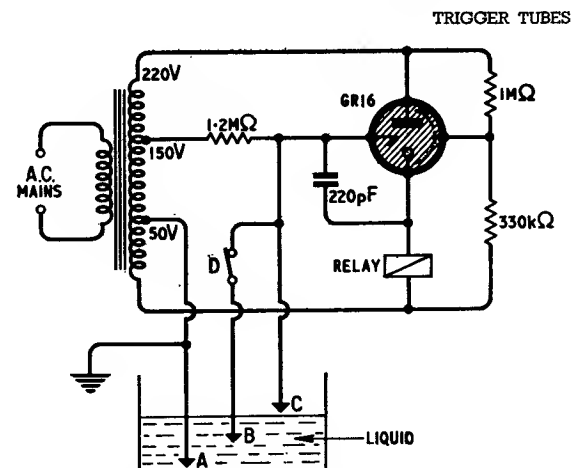
Fig. 3.6. A circuit for controlling the level of a liquid.

of the points B and C. The trigger potential will be little greater than that of the 50 V tapping on the mains transformer during the half cycles when the tube anode is positive if the liquid level is high. The trigger tube does not therefore pass a current.

When the liquid level falls below the point B, the potential of the trigger electrode becomes almost the same as that of the 150 V tapping on the mains transformer and the tube will therefore strike during alternate half cycles of the mains supply voltage when the anode and trigger are positive. The relay is therefore energised. The contacts D are part of the relay and open when the latter is energised. Thus as the liquid level rises, the trigger electrode is not connected to the 50 V tapping via the liquid until the level of the latter reaches the point C. The pumping of the liquid therefore ceases at this point.

The relay employed in this circuit contains some shorted turns which prevent 'chattering' when pulses of current pass through it; no capacitor is therefore required in parallel with this type of relay.

ELECTRIC FENCE CONTROL

A somewhat similar type of circuit can be used to control the application of the high voltage to an electric fence. No power is consumed from the battery unless an animal touches the fence, the resistance of the animal between the fence and the ground constituting one of the sections of a potential divider. The trigger tube is controlled by this potential divider and fires only when an animal

touches the fence. A relay in the trigger tube circuit then closes and this results in the high voltage being applied to the fence.

PROTECTION CIRCUITS

Protection circuits are designed to safeguard equipment against some specific hazard, for example, to protect electronic equipment against transient high voltages or currents. Trigger tubes are especially suitable for this type of circuit, since they consume no power and are completely inoperative during quiescent periods.

The basic circuit for the protection of an expensive transmitting valve against overload is shown in Fig. 3.7. Normally the screen
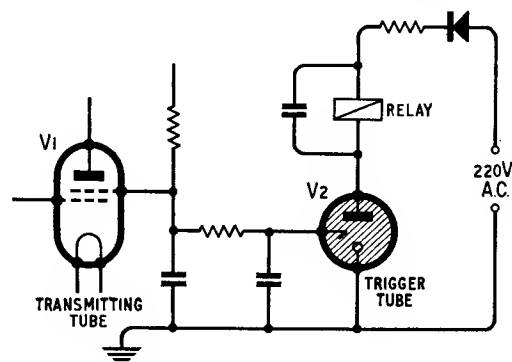
Fig. 3.7. A circuit for the protection of a transmitting tube.

grid voltage of the transmitting tube, $V1$, will be great enough to cause the trigger tube $V2$ to ignite during each alternate half cycle of the mains supply when the anode of $V2$ is positive. During overloads, however, the anode and screen currents of $V1$ are increased and hence the screen grid potential falls. The trigger tube no longer ignites and therefore the relay in the anode circuit opens and removes the power from the transmitting valve.

TIMING CIRCUITS

Simple timing circuits which depend on the time taken for a capacitor to charge through a resistor can be constructed using trigger tubes. Such circuits are used in process control in industry, as photographic timers, etc. Trigger tubes can also be used in more complicated timing circuits which provide a delay equal to a

predetermined number of half cycles of the mains supply frequency. They are known as synchronous timers and basically consist of circuits for counting the half cycles of the mains frequency. Synchronous timers are especially suitable for controlling the time for which a welding current flows, but will not be discussed further here.

The basic circuit of a resistance-capacitance timer is shown in Fig. 3.8. As soon as the voltage V_T is applied to the trigger circuit
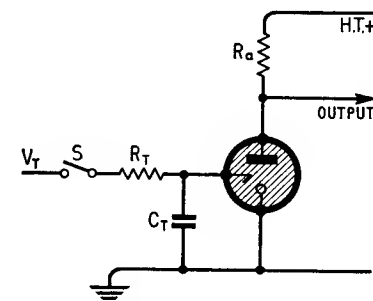
Fig. 3.8. The basic circuit of an RC timer.

by the closing of the switch S, the capacitor C_T commences to charge through the resistor R_T. When the potential across this capacitor reaches the trigger to cathode striking potential, V_s', of the tube, ignition will occur and a negative going output pulse will occur at the anode. If desired the resistor R_a may be replaced by a suitable relay.

The time, t, which passes after the closure of the switch S before the trigger potential reaches the trigger striking potential, V_s', is given by the equation:

$$t = R_T C_T \log_e \frac{V_T}{(V_T - V_s')}$$

The maximum time delay which can be obtained with reasonable accuracy is limited by practical considerations to about an hour or so. For longer times mechanical timers are more economical. The minimum time delay is a few milliseconds provided that a relay is not employed. In timing circuits using a relay, the minimum time will be limited by the operating time of the relay to about ¼ sec, but a greater percentage accuracy will be obtained if the delay time is somewhat longer than this.

If accurate time delays are required, the components C_T and R_T should be high stability components. Electrolytic capacitors are not suitable for use as C_T, since their leakage resistance and the

variation of their capacitance value would affect the operation of the circuit. A trigger tube which has a stable trigger striking voltage should be selected for accurate timing. In addition the potential V_T should be stabilised in accurate work.

The ratio V_s'/V_T is usually selected so that it lies in the range 0·5 to 0·8. If the value is above 0·8, the accuracy is much reduced. For values of C_T exceeding about 0·01 μF, an additional resistor of a few thousand ohms must be placed between this capacitor and
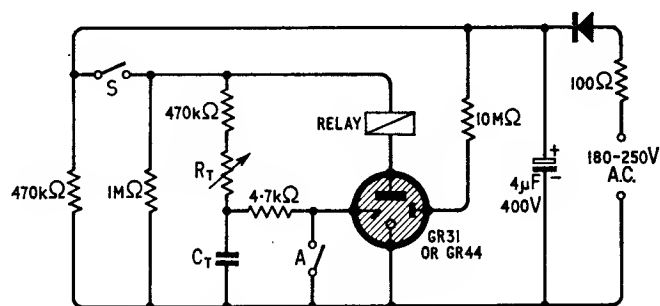
Fig. 3.9. A simple timing circuit.

the trigger electrode to limit the current flowing in the trigger circuit.

A simple timing circuit designed by the Cerberus Company for their GR31 or GR44 tube is shown in Fig. 3.9. When the contacts S are closed, the capacitor C_T commences to charge via the resistor R_T. The latter is a variable resistor of some megohms, the value of which is used to control the time delay. The contacts A on the relay serve to discharge the capacitor C_T when the tube conducts. When the contacts S are opened, conduction in the trigger tube will cease and the capacitor C_T will be discharged ready for the next operation. The anode which is shown on the right-hand side of the tube connected to the 10 MΩ resistor is a priming anode.

For some applications it is desirable that the time delay should be inversely proportional to some power of the mains supply voltage. If, for example, it is desired to produce a certain amount of heat in a resistive element, the time for which the current flows in the element should be inversely proportional to the square of the voltage. Similarly if it is required to produce a certain constant amount of light using a tungsten filament bulb, the time for which the current flows through the bulb must be inversely proportional to a high power of the applied voltage. Timing circuits have been designed using trigger tubes which satisfy these requirements.

COUNTING CIRCUITS

Trigger tubes have been widely used in circuits which count electrical pulses. Although trigger tube counting circuits tend to be more versatile than the circuits employing stepping tubes (see Chapter 6), the stepping tube circuits are often preferred for simplicity.

The basic circuit of a trigger tube ring counter is shown in Fig. 3.10. At any time only one of the tubes is conducting; let us assume that it is V_0. The flow of current through the cathode resistor of this tube develops a voltage across this resistor which is used to bias
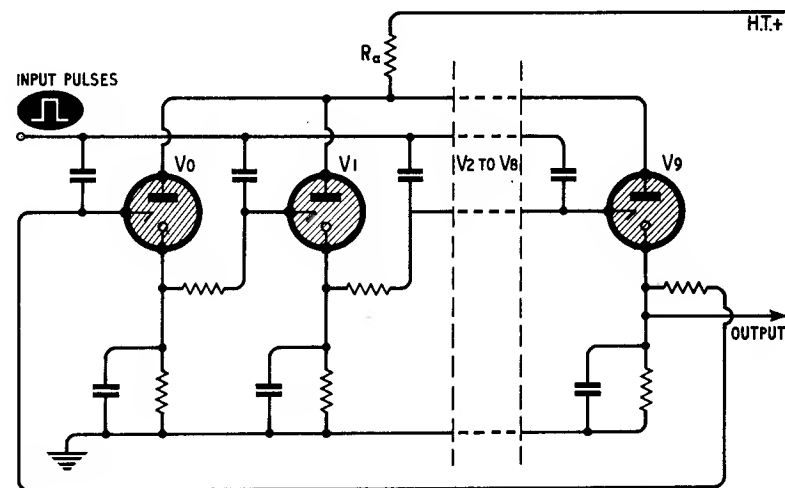
Fig. 3.10. A simple ring counting circuit.

the trigger electrode of V_1. However, this bias is not great enough to switch the tube into its conducting state.

The input pulses to be counted are fed simultaneously to the trigger electrodes of each of the tubes via capacitors. The amplitude of the input pulses is not itself great enough to cause a tube to fire, but it will do so in conjunction with the bias applied from the cathode resistor of a conducting tube. Thus V_1 is ignited when a pulse is received, since it is the only tube receiving the bias. The firing of V_1 causes the common anode voltage to decrease owing to the additional current flowing through the common anode resistor, R_a. The voltage across V_0 is less than that across V_1 when the latter tube has just ignited, since the capacitor in the cathode circuit of V_0 is charged, but that in the cathode circuit of V_1 has not had time

to charge. Thus V_0 is extinguished preferentially to V_1 as the common anode voltage falls. The glow in V_1 shows a count has been recorded.

A second pulse will transfer the glow to V_2 (not shown in Fig. 3.10) by the same mechanism. When nine pulses have been applied to the input, V_9 will glow. A further pulse will cause the glow to return to V_0. Thus the circuit counts on a scale of ten, but any reasonable number of tubes can be included in the ring so that counting on any other scale can be carried out. The output pulses from the circuit of Fig. 3.10 may be fed to another ring counter which counts the number of tens.

REVERSIBLE COUNTING

Reversible trigger tube counting circuits can be constructed using tubes which have twin trigger electrodes. A typical example is the Mullard circuit for their Z700W tubes (equivalent to the Philips type Z70W) shown in Fig. 3.11. The priming cathodes employed in these tubes are connected via 18 MΩ resistors to earth, the priming current being about 3 μA. The circuit is symmetrical in each direction. When suitable pulses are applied to the 'add'
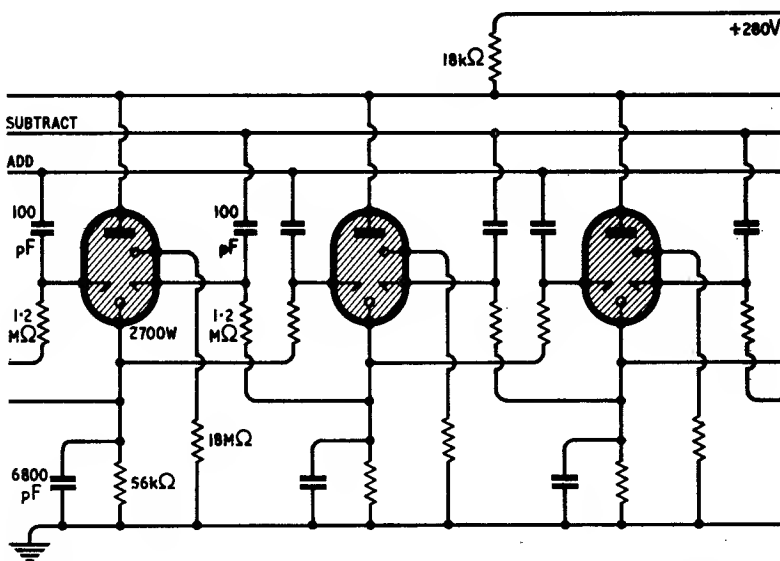
Fig. 3.11. A reversible counting circuit; the values not shown are the same as those in the first stage.

input, the glow moves one position to the next tube. Thus the indicated count is increased by unity. A similar pulse to the 'subtract' input will cause the indicated count to decrease by unity.

The principle of operation of the circuit is the same as that of the circuit of Fig. 3.10. The stages at each end of the circuit may be connected to form a reversible ring counter, but two connections will be needed to close the ring. The input pulses should be of about 100 V in amplitude and of about 20 μsec in duration. The maximum counting speed is a few thousand pulses per second, this speed depending on the component tolerances and the tolerance of the H.T. supply voltage.

Another type of reversible counting circuit employing tubes with twin triggers has been developed by the Cerberus Company. In this circuit the potential acquired by each trigger electrode of a conducting tube is used as a bias voltage for a neighbouring tube.

Other types of trigger tube counting circuit can be constructed, including binary counting circuits which are effectively rings of two tubes. The so called biquinary circuits employ a ring of two and a ring of five tubes to form a scale of ten.

OTHER USES

Trigger tubes can be employed for a wide variety of other applications involving switching, including simple logic circuits, pulse generation and speech switching in telephone circuits. The use of trigger tubes for voltage stabilisation will be discussed in Chapter 5 and their application in driving numerical indicator tubes in Chapter 7. A special type of trigger tube has been developed by the Cerberus Company for use in their ionisation smoke detectors which give an early warning of a fire.

ELECTRONIC TOUCH BUTTON

The electronic touch button manufactured by the Cerberus Company is a special type of trigger tube which is switched to the conducting state by the touch of a person's finger on an external control electrode which is placed at the end of the tube. After the electrode has been touched, the tube emits a visible glow until the H.T. supply is momentarily interrupted for a time exceeding the tube deionisation time. The current flowing through the tube may be used to operate a relay. A typical application of this tube is its use in the control panels of lifts for selecting the floor at which the

passenger wishes to alight. When the tube corresponding to the selected floor is touched, it continues to glow until the lift reaches that floor. The tubes are also used in control panels.

A typical circuit using the Cerberus GK11 touch button which has been designed by the manufacturers of this tube is shown in
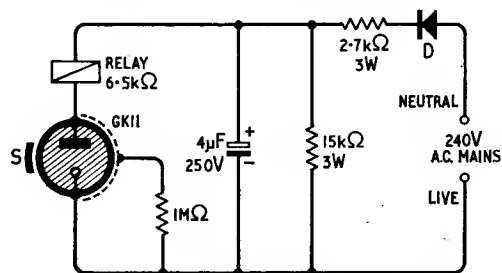
Fig. 3.12. A touch controlled relay circuit.

Fig. 3.12. The external screening around this tube is connected to the 'live' or 'phase' lead of the mains supply via a 1 MΩ resistor. When the external control electrode, S, is touched by the hand or is earthed, there is an alternating potential of nearly 240 V between this electrode and the tube cathode. The current which flows produces enough ions to ignite the main gap. Even if the tube is touched by a hand covered with a glove, the effective capacitance between the external electrode and earth normally exceeds 5 pF and this is adequate to fire the tube.

The GK11 tube employs a coated cathode. The cathode current range of 8 to 15 mA is adequate for the operation of most relays.

In the circuit of Fig. 3.13, one of the two GK11 tubes is conducting at any one time. If the tube which is not conducting is touched, it
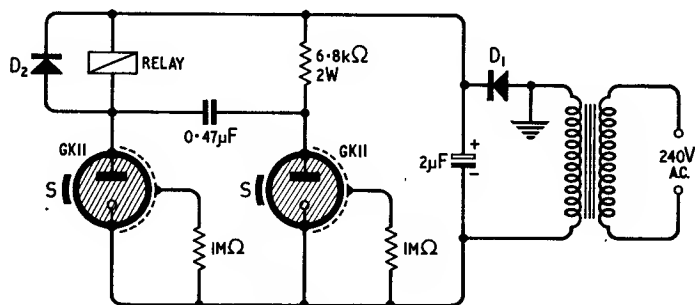
Fig. 3.13. An 'on–off' touch control circuit.

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will be switched to the conducting state. The relay in the anode circuit of the left-hand tube is energised when this tube is conducting. When either tube is switched to the conducting state, the fall in the anode potential of that tube is applied to the other tube via the capacitor connecting the tube anodes. Thus the anode potential of this latter tube falls below the maintaining voltage and the tube is extinguished.

SUGGESTIONS FOR EXPERIMENTS WITH TRIGGER TUBES

EXPERIMENT 1 *Trigger tube characteristics*

Anode-cathode gap

Connect a Hivac XC18 trigger tube as shown in Fig. 3.14. Leaving the left hand side of the microammeter unconnected at first,
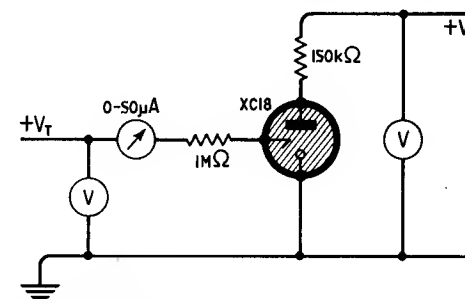
Fig. 3.14. A circuit for the measurement of trigger tube characteristics. (When necessary the voltmeters should be connected to the anode and trigger.)

gradually increase the anode supply voltage, $+V_b$, until the tube strikes and then decrease it until the glow is extinguished. Measure the striking and maintaining voltages of the anode to cathode gap as in experiment 1 of Chapter 2.

Trigger-cathode gap

Determine the striking and maintaining voltages of the trigger to cathode gap by gradually increasing the trigger supply voltage, V_T, until the tube strikes and then reducing this voltage again. The anode supply voltage can be left at zero. Note whether the trigger

55

striking voltage is much different from the trigger maintaining voltage.

The trigger tube as a whole

Adjust the anode supply voltage to $+180$ V. Gradually increase the trigger voltage until both gaps strike. Reduce the trigger voltage to zero; is the anode current affected by this reduction? Ascertain whether the trigger striking voltage is dependent on the anode voltage.

Increase the trigger potential with the anode voltage at zero until the trigger to cathode gap strikes. Adjust the trigger current to a suitable value and then increase the anode potential slowly until the anode-cathode gap strikes. Note the anode potential immediately *before* the gap strikes. Repeat with other values of trigger current and plot the transfer characteristic (see Fig. 3.1).

EXPERIMENT 2. *Trigger tube applications*

One of the most suitable experiments on trigger tube applications is the design and construction of a simple resistance-capacitance timing circuit. The expected performance should be compared with that measured experimentally.

SUGGESTIONS FOR FURTHER READING

TRIGGER TUBE CIRCUIT DESIGN
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'Das Entwerfen von Schaltungen mit Kaltkathodenröhren', *Cerberus Elektronik*, 5 (October 1957).

TRIGGER TUBE CIRCUITS
R. S. SIDOROWICZ, 'Cold cathode tubes for automation', *Electron. Eng.*, 33, 397, 138 (1961); 33, 398, 232 (1961); 33, 399, 296 (1961).
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'Philips Cold Cathode Trigger Tubes for Industrial Applications', Philips Electron Tube Division publication 20/092/D/E-1-62.
'Trigger tubes', *Electron. Appl. Bull.*, 16, 1, 1 (1955–56).
G. O. CROWTHER AND M. J. POTTER, 'Timing circuits using the cold cathode stable trigger tube Z803U', *Mullard Tech. Commun.*, 2, 114 (1955).
R. HÜBNER, 'Kaltkatodenrelaisröhren und Dekadenzählröhren', Dr. A. Hüthig Verlag, Heidelberg (1965).

4
The Glow Thyratron

The GT21 glow thyratron is a rather unique type of tube manufactured by the Cerberus Company of Switzerland; it has many properties in common with ordinary trigger tubes. The glow thyratron has the advantage that it can be switched to the conducting state by potentials very much smaller than those required to operate a conventional trigger tube. The glow thyratron is very suitable for the operation of a relay, the maximum current being 40 mA.

PRINCIPLES OF OPERATION

A cross sectional diagram of the electrode structure of a glow thyratron is shown in Fig. 4.1. A continuous discharge takes place between the auxiliary electrode, H, and the main cathode, K, the latter acting as the anode for the auxiliary discharge. Electrons from this discharge penetrate through a hole in the cathode. If the grid G is biased with a negative potential of not less than about 5 V with respect to the cathode, the electrons will be repelled back to the cathode. If, however, the grid potential is made less negative, the electrons are accelerated and pass through the holes in the grid towards the anode. Gas multiplication occurs in the space between the grid and anode and the main discharge is thus initiated.

Conduction in the main gap of a trigger tube is initiated by the firing of an auxiliary discharge, but in the glow thyratron it is accomplished by the controlled release of electrons from the priming discharge into the space between the grid and the anode.

The firing characteristic of a glow thyratron is shown in Fig. 4.2. The main gap will conduct if the operating point crosses either of
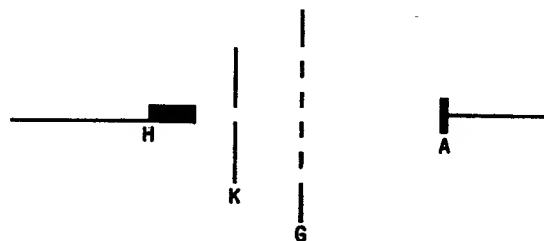
Fig. 4.1. The electrode structure of the glow thyratron.

the lines shown, but in practice it should not be allowed to cross the lower line, since this would result in reverse conduction. The tube is operated at the part of the upper curve where the slope is large. When the grid becomes less negative, the steep part of the curve is crossed from left to right and the main gap fires.

For positive grid voltages up to about 15 V, the characteristic rises somewhat, since the positive grid tends to attract electrons and remove them from the gas so that they do not give rise to gas amplification in the space between the grid and anode. At grid
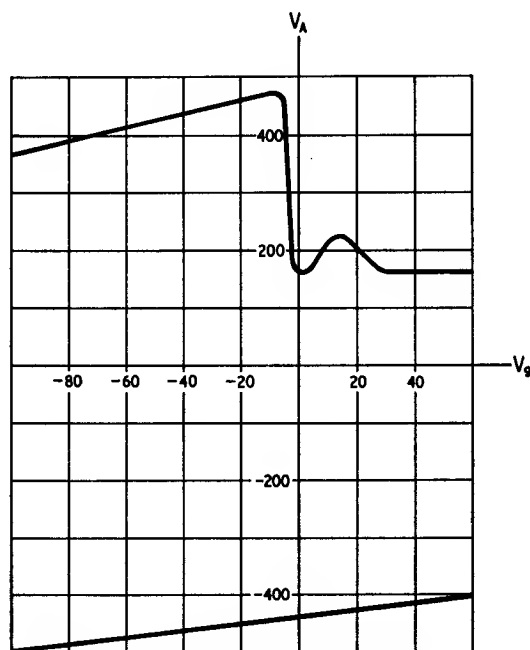
Fig. 4.2. The glow thyratron firing characteristic.

voltages exceeding about +15 V the auxiliary discharge will form between the auxiliary cathode and the grid. If the grid receives a negative potential exceeding 80 V with respect to the main cathode, it may act as a cathode, but this mode of operation should be avoided. Similarly the grid potential should not exceed +50 V with respect to the cathode.

Once a glow thyratron has been switched to the conducting state, the potential of the grid electrode no longer controls the flow of the main anode current. As in the case of a trigger tube, the glow thyratron is extinguished by reducing the main anode potential below the maintaining voltage of the main gap for a time exceeding the deionisation time of the tube.

The auxiliary discharge should consist of a current in the range of 100 to 250 μA. The firing characteristics of the tube are virtually independent of the value of this current provided that it is within the recommended range. The auxiliary cathode, *H*, is returned via a current limiting resistor to a suitable source of negative potential.

When the main anode conducts, the auxiliary discharge takes place between this anode and the auxiliary cathode; the potential of the latter electrode is raised to approximately the potential of the main cathode and the auxiliary discharge current is correspondingly increased.

The grid of the glow thyratron acts as a probe near to the auxiliary discharge when the main gap is not conducting and therefore a small grid current (normally less than a microamp) will pass. In a conducting tube the grid behaves as a probe in the plasma and effectively acts as a source of about 100 V of an equivalent series resistance of about 100 kΩ.

The grid current will result in the grid potential being somewhat different from that applied to the grid resistor. However, if the value of this resistor does not exceed a few hundred thousand ohms, the effect will be small.

The tolerance in the grid potential at which ignition occurs is less than one volt from tube to tube. Glow thyratrons show a thermal hysteresis effect which results in a slightly greater negative grid potential being required to prevent the tube from conducting immediately after it has been passing an appreciable anode current. However, there is little change in the grid voltage at which firing occurs as the ambient temperature varies over the range of —30°C to +90°C.

Apart from the fact that the GT21 glow thyratron can be controlled by small potentials of about 5 V (which enables it to be operated from transistor circuits), it has a number of attractive

features. A pure molybdenum cathode is employed and this results in the tube having very stable characteristics and a long life. The high anode breakdown voltage (about 450 V) and the high cathode current rating of 40 mA enable it to control loads of up to about 15 W. The presence of the auxiliary discharge enables ionisation times of less than 1 μsec to be obtained at fairly high anode voltages.

APPLICATIONS OF THE GLOW THYRATRON

The following simple circuits have been selected from those published by the manufacturers of the glow thyratron. They show how
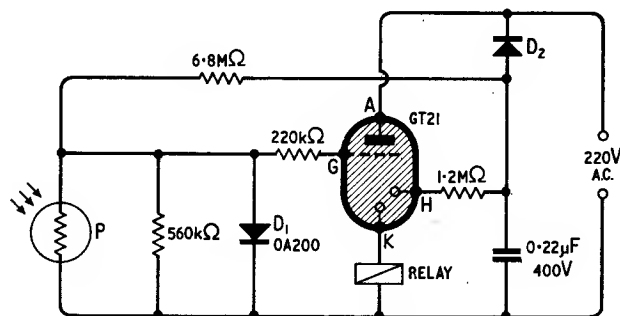
Fig. 4.3. A circuit for controlling a relay by a light beam.

the tube can be employed to operate a relay from small signals. The anodes of the glow thyratrons are supplied with an a.c. signal so that the main discharge is automatically extinguished during each alternate half cycle of the mains supply when the anode is negative with respect to the cathode. The relays employed in these circuits should have a suitable number of shorted turns in their windings so that they will operate satisfactorily from the half wave rectified waveform passing through the tube. No mains transformer is required in these circuits.

RELAY CONTROL BY LIGHT BEAM

A simple circuit for the control of a relay by means of a beam of light is shown in Fig. 4.3. The diode D_2 rectifies the mains supply voltage, the peaks of the alternate half cycles being smoothed by the 0·22 μF capacitor. The resulting negative potential is used to supply both the auxiliary cathode, H, and the photodiode, P.

When P is in darkness, it has a relatively high impedance and, therefore, an appreciable negative potential is developed across it. This potential is fed to the grid of the GT21 and prevents the tube from conducting. When light falls onto the photodiode, the potential across this diode falls. This results in the grid voltage of the GT21 becoming very small. The main gap of the tube, therefore, fires and operates the relay.

The diode D_1 short circuits the positive grid voltage of the tube when it is conducting. The rectifier diode, D_2, should have a peak inverse voltage rating of not less than 700 V, but the forward rating need only be 5 mA. The Texas Instruments H11 photodiode or the Siemens type TP51 11 is suitable for use in this circuit.

THERMOSTAT CIRCUIT

The circuit of Fig. 4.4 may be used to switch a heating element on and off in order to keep the temperature of an enclosure constant.
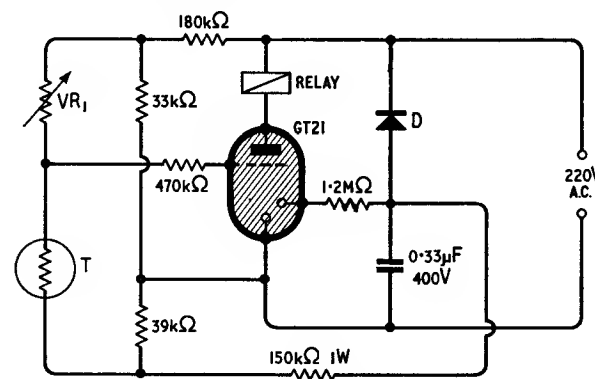
Fig. 4.4. A thermostat circuit.

A thermistor is used as the temperature sensing element, but the operating temperature range is limited to about −25°C to 150°C. The temperature at which the relay operates is controlled by the setting of the potentiometer VR_1.

The resistance of the thermistor decreases with increase of temperature. The thermistor T in Fig. 4.4 is fed from the negative half wave rectified supply via the 150 kΩ resistor. As it becomes cooler, its resistance increases and the potential applied to the grid of the GT21 glow thyratron becomes less negative. When the tube fires, the relay in its anode circuit switches on a heating element to raise
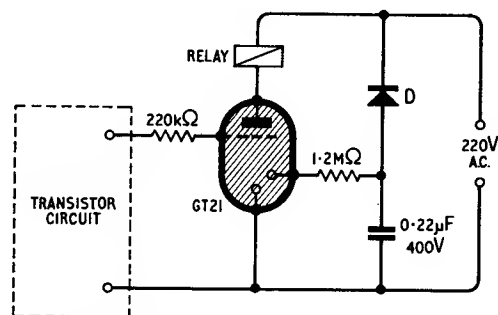
Fig. 4.5. Control of a glow thyratron by a transistor circuit.

the temperature of the enclosure containing the thermostat. The remainder of the circuit functions in the same way as Fig. 4.3.

In order to prevent the circuit from switching on and off too frequently, a capacitor of about 6,800 pF may be placed across the 470 kΩ resistor in the grid circuit. The temperature at which the relay is energised then becomes somewhat lower than the temperature at which it is de-energised after the heater has been operating. The capacitor becomes charged after the tube fires owing to the grid current which flows. The charge of the capacitor assists in causing the tube to ignite in the next half cycle of the mains voltage at which the anode is positive.

The temperature at which the glow thyratron conducts varies somewhat with the mains voltage.

CONTROL BY A TRANSISTOR CIRCUIT

The circuit of Fig. 4.5 shows how a glow thyratron may be controlled by a transistor circuit. The output impedance of the transistor circuit should be about 20 kΩ. The circuit will switch on when the grid voltage is not more negative than —0·5 V with respect to the cathode and will switch off when it is more negative than —5 V. The collector circuits of transistor bistable stages normally meet these requirements.

SUGGESTIONS FOR FURTHER READING

M. VOLLENWEIDER, 'The glow thyratron', *I.E.R.E. Symp.*, Cambridge (1964).
R. A. DÜRR, 'Glimm-thyratrons', *Der Elektroniker*, 3, 29 (1962).

5
Voltage Stabilisation

There are four main ways in which cold cathode tubes may be employed to stabilise a voltage against variations of either the supply voltage or of the load current.

1. A voltage stabiliser tube may be used operating in the normal glow region of the characteristic. Such tubes can be employed in extremely simple circuits to provide stabilised outputs in the range of about 55 to 300 V. Higher output voltages may be obtained by the use of several stabiliser tubes in series or of a single tube containing more than one discharge gap.
2. Corona voltage stabiliser tubes enable very simple circuits to be constructed which can provide stabilised outputs in the range of 340 to 30,000 V. However, they are suitable only for use in circuits in which the load current variations will be quite small (normally less than 1 mA).
3. Glow stabiliser or corona stabiliser tubes may be used in conjunction with thermionic valves. The cold cathode tube is used as a source of a reference voltage and does not effect stabilisation of the output. Such circuits can be designed for the stabilisation of a wide range of voltages to a high degree of accuracy even if the output current variations are quite large.
4. Voltage stabiliser circuits can be designed using trigger tubes. This is a useful technique when a fairly stable output voltage is required at currents of some milliamps.

GLOW STABILISER TUBES

Many types of glow discharge stabiliser tube contain a wire anode surrounded by a cylindrical cathode, although planar cathodes are

sometimes used. The cathode may consist of a pure metal or it may be coated with a material of low work function; tubes with pure metal cathodes have extremely stable characteristics. The gas filling is often neon mixed with a little argon, but mixtures containing helium are sometimes used. Modern stabiliser tubes are usually miniature plug-in types or sub-miniature wire ended tubes.

Glow discharge tubes usually operate in the normal glow region of the characteristic. It can be seen from Fig. 1.1 that in this region (marked F to G) the voltage across the tube is almost independent of the current flowing. Some tubes are operated just inside the abnormal glow region.

Glow discharge stabiliser tubes may be divided into two main types. The so called 'stabiliser' tubes are designed so that they will operate over a fairly large current range, whereas the 'reference' tubes are intended to provide a reference voltage of greater stability when they are operated within a more closely specified current range. Most reference tubes employ pure metal cathodes. Reference tubes provide the best possible stability at constant loading; stabiliser tubes provide a lower output impedance for variable loads.

BASIC CIRCUIT

The basic circuit for the use of a glow discharge stabiliser or reference tube is shown in Fig. 5.1. The voltage across the load resistor
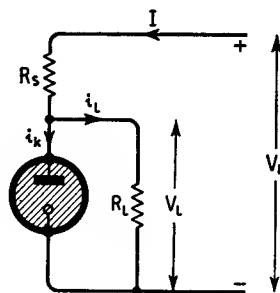
Fig. 5.1. The basic voltage stabiliser circuit.

is the same as the voltage across the tube and is equal to the supply voltage, V_b, minus the voltage drop across the series resistor, R_s.

$$V_L = V_b - IR_s$$

where V_L is the voltage across the load resistor and I is the total current flowing. V_b is usually between one and a half and three times the value of V_L.

If the supply voltage V_b changes, V_L will remain almost constant and therefore the voltage across the anode resistor must change. The total current, I, and the current passing through the stabiliser tube, i_k, each change by the same amount so that the load current remains unaffected.

If the load resistance R_L increases, the load current, i_L, must decrease if the voltage across the load is to remain constant. Thus i_k must increase by the same amount as i_L decreases, I remaining constant. The circuit should be designed so that the tube will operate in the current range recommended by the manufacturers as R_L changes within the expected limits.

An ideal voltage stabiliser or reference tube should show no change in maintaining voltage with the current flowing through it or with changes of temperature, or on ageing, etc. However, the maintaining voltage of practical tubes is affected by such factors.

Changes in the current passing through the tube within the recommended operating range will cause small changes in the maintaining voltage. The internal resistance or differential resistance, R_d, is defined as the rate of change of the maintaining voltage with current.

$$R_d = \frac{\delta V_m}{\delta i_k}$$

If the current flowing through the tube is altered by a small amount, the resulting change in the maintaining voltage will be equal to this change multiplied by R_d. In practice matters are not quite so simple, since the value of R_d varies somewhat with the current flowing through the tube. Nevertheless R_d is a useful parameter in approximate calculations on the performance of voltage stabiliser tubes. The value of R_d is usually between about 100 and 500 Ω. This is approximately equal to the output resistance of the circuit.

The regulation of a tube is normally defined as the change in the maintaining voltage as the current passing through the tube changes from its minimum to its maximum rated value.

At high frequencies the tube impedance increases, since a change in the cathode current takes time to produce a change in the space charge. The tube impedance can be reduced by connecting a capacitor of about 0·1 μF across it, but care must be taken to avoid the possibility of relaxation oscillations occurring (see Chapter 2).

In addition to the fairly steady change of maintaining voltage with current, some stabiliser tubes show sudden changes in their maintaining voltage at one or more points in their operating current range. These changes are due to non-uniformities in the cathode surface which result in small negative resistance regions of the

characteristic being formed. Such voltage jumps may have an amplitude ranging from some millivolts to several volts. They do not necessarily occur at the same point for increasing and decreasing cathode currents. Reference tubes operating in the abnormal glow region do not show this effect.

Noise is present in voltage stabiliser tubes owing to random effects occurring in the discharge, such as gas amplification and electron emission by ionic bombardment. The noise amplitude increases as the cathode current decreases, especially near to the minimum rated value of the cathode current. The noise voltage is typically in the range 0·05 to 5 mV. Noise can be reduced by placing a capacitor in parallel with the tube.

The maintaining voltage of most tubes shows a negative temperature coefficient of the order of 10 mV per °C. There may be an initial drift of the order of 1 per cent for some minutes after conduction has commenced.

Stabiliser tubes for the lowest maintaining voltages (about 55 V) employ a barium cathode and are filled with neon containing about 0·5 per cent of argon. The same gas mixture will give a maintaining voltage of about 85 V when used with a molybdenum cathode. A helium gas filling containing about 0·5 per cent of argon will provide higher maintaining voltages with any specified type of cathode. This mixture is used with cathodes of sputtered nickel to produce tubes with maintaining voltages of about 150 V. The final adjustment of the maintaining voltage may be made by altering the composition of the gas filling.

STABILISATION FACTOR

The stabilisation factor (or smoothing factor) of a tube is the factor by which variations of the supply voltage, V_b, are reduced by the circuit. That is, the stabilisation factor, S, is defined by the equation:

$$S = \frac{\delta V_b}{\delta V_m} \qquad (5.1)$$

However, the stabilisation factor is sometimes defined in a slightly different way as the ratio of the percentage fluctuation of the input voltage to the percentage fluctuation of the output voltage. This stabilisation factor, S', may, therefore, be defined in terms of the following equation:

$$S' = \left(\frac{\delta V_b}{V_b}\right) \bigg/ \left(\frac{\delta V_m}{V_m}\right) \qquad (5.2)$$

Hence

$$S' = \left(\frac{V_m}{V_b}\right) S$$

Thus S' is somewhat smaller than S.

If it is assumed that the differential resistance of the tube is constant over the operating range, the stabilisation factor, S, may be calculated in the following way for a tube operating in the circuit of Fig. 5.1.

$$I = i_k + i_L$$

$$\delta I = \delta i_k + \delta i_L \qquad (5.3)$$

But $\delta I = \dfrac{\delta(V_b - V_m)}{R_s}$, $\delta V_m = \delta i_k R_d$ and $\delta i_L = \dfrac{\delta V_m}{R_L}$

Hence, substituting for δI, δi_k and δi_L in equation 5.3:

$$\frac{\delta(V_b - V_m)}{R_s} = \frac{\delta V_m}{R_d} + \frac{\delta V_m}{R_L}$$

$$\frac{(\delta V_b - \delta V_m)}{R_s} = \delta V_m \left(\frac{1}{R_d} + \frac{1}{R_L}\right)$$

$$\frac{\delta V_b - \delta V_m}{\delta V_m} = R_s \left(\frac{1}{R_d} + \frac{1}{R_L}\right)$$

$$S = \frac{\delta V_b}{\delta V_m} = R_s \left(\frac{1}{R_d} + \frac{1}{R_L}\right) + 1 \qquad (5.4)$$

If $R_L \gg R_d$, the following approximation can be made,

$$S \simeq \frac{R_s}{R_d} + 1 \qquad (5.5)$$

or, as R_s is usually much greater than R_d,

$$S \simeq \frac{R_s}{R_d}$$

R_s is usually some tens of thousands of ohms, whilst R_d is typically of the order of 100 Ω. Thus S ranges from about 20 to 400. Mains voltage changes of 35 V (about 15 per cent) will result, in a typical case, in changes of the stabilised output of the order of 0·5 V (about 0·2 per cent).

As $R_s = \dfrac{(V_b - V_m)}{I}$, equation 5.5 may be transformed into the following equation:

$$S \simeq \frac{(V_b - V_m)}{IR_d} + 1$$

or

$$S \simeq \frac{(V_b - V_m)}{IR_d}$$

Thus circuits which operate at a low current tend to have a high stabilisation factor.

STRIKING

A voltage stabiliser tube will not function until it has been switched to the conducting state by the applied voltage, V_b. In order for this to happen, the voltage across the tube must exceed the striking voltage, V_s. Indeed, there may be some delay in the striking of some tubes when a voltage exceeding V_s is applied, especially if a tube is being operated in total darkness. Other tubes contain a radioactive priming agent to facilitate striking.

The resistors R_s and R_L of Fig. 5.1 act as a potential divider and therefore, when the supply voltage V_b is first applied and i_k is zero, the voltage across the tube is:

$$\frac{R_L}{(R_s + R_L)} V_b$$

Thus the condition for reliable striking is:

$$V_s < \frac{R_L}{(R_s + R_L)} V_b$$

Allowing for resistor and supply voltage tolerances:

$$V_s < \left\{ \frac{R_{L\,(min)}}{R_{s\,(max)} + R_{L\,(min)}} \right\} V_{b\,(min)}$$

or

$$R_{s\,(max)} = \left(\frac{V_{b\,(min)}}{V_s} - 1 \right) R_{L\,(min)} \tag{5.6}$$

If R_s exceeds this value, the tube may not strike within a reasonable time. Most stabiliser tubes employ a Penning mixture in order to keep V_s low.

PRIMED TUBES

If the load current is large, equation 5.6 imposes a rather severe limitation on the design of the circuit. In such cases primed voltage stabiliser tubes may be employed. These have an additional priming anode placed relatively close to a part of the cathode so that striking will occur between these electrodes at an applied potential smaller than that required to produce striking of the main gap. When the supply voltages are first applied, the discharge is initiated between the priming anode and the cathode, but the resulting ions quickly cause the main discharge to form.

The anode voltage which must be applied to a primed stabiliser tube to ensure that the main gap conducts is little more than the maintaining voltage of the tube; it may be referred to as 'the anode take over voltage'. The value of this voltage should be inserted into equation 5.6 in place of V_s when a primed stabiliser tube is being used. In practice the striking conditions for a primed stabiliser tube will normally be satisfied when the series resistor, R_s, is selected to satisfy other circuit requirements. The priming current is often of the order of 0·5 mA and may help to improve the operating characteristic near to the minimum current rating.

Some tubes containing a cylindrical cathode surrounding a wire anode employ a wire attached to the inside of the cathode pointing towards the anode as a priming electrode. Striking occurs between the wire and the anode at a voltage which is little greater than the maintaining voltage, but little current can flow to the wire owing to its small surface area.

CURRENT LIMITATIONS

The maximum current rating of a glow stabiliser tube is set either by the heat dissipation or by the cathode damage which would occur if this rating were exceeded. Almost all of the heat comes from the negative glow. The minimum current rating is set by the need to maintain steady ionisation in the tube.

The maximum and minimum values of the series resistor R_s of Fig. 5.1 may be found in the following way,

$$R_s I = R_s(i_k + i_L) = V_b - V_m$$

$$R_s = \frac{(V_b - V_m)}{(i_k + i_L)}$$

If V_m is assumed to have a definite value of zero tolerance,

$$R_{s\,(\text{max})} = \frac{(V_{b\,(\text{min})} - V_m)}{i_{k\,(\text{min})} + i_{L\,(\text{max})}} \qquad (5.7)$$

However, the value of $R_{s\,(\text{max})}$ must also satisfy equation 5.6. Similarly

$$R_{s\,(\text{min})} = \frac{(V_{b\,(\text{max})} - V_m)}{i_{k\,(\text{max})} + i_{L\,(\text{min})}} \qquad (5.8)$$

If the load on a voltage stabiliser comprises a thermionic valve circuit, the current passing through the stabiliser tube may exceed the maximum value immediately after switching on whilst the valves are warming up. One manufacturer states that a current up to 2·5 times the maximum permissible continuous current may be taken by the stabiliser tube for a period of up to ten seconds, whereas some manufacturers quote a figure for the maximum permissible peak current which may pass for a stated time. If I_0 is the maximum permissible initial current during the warming up period when no load current is being drawn,

$$\frac{V_{b\,(\text{max})} - V_m}{R_{s\,(\text{min})}} \ll I_0$$

The characteristics of voltage stabiliser tubes are likely to be affected if a current passes through the tube in the reverse direction. For this reason the maximum reverse voltage applied to the tube should not exceed $0.9V_m$.

TUBES IN SERIES

Voltage stabiliser tubes may be connected in series (as shown in Fig. 5.2) in order to obtain a greater stabilised output voltage. If all of the tubes are not of the same type, it is important to ensure that there is an adequate overlap in the current ranges of the tubes used.

The striking voltage of n tubes connected in series is n times that of a single tube; however, this striking voltage can be reduced by connecting resistors of a comparatively high value (about 500 kΩ) between the junctions of the tubes and one of the power supply lines as shown. R_2 shunts V_2 and V_3, so V_1 will strike as soon as its anode potential exceeds the tube striking potential. Similarly R_1 shunts V_3, so V_2 also strikes readily. When V_1 and V_2 have both struck, the voltage across V_3 is equal to the voltage across the load minus the sum of the maintaining voltages of V_1 and V_2; this should be adequate to ensure that V_3 will strike. If V_3 has a priming anode,
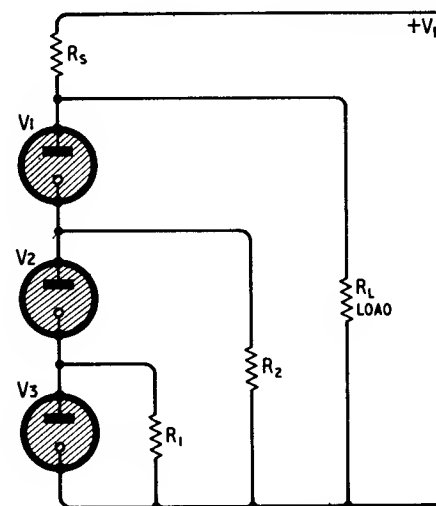
Fig. 5.2. A series connected stabiliser circuit.

it should be connected via a suitable current limiting resistor to the positive power supply line.

Voltage stabiliser tubes should not normally be connected in parallel, since it is probable that only one of the tubes will strike. As the input voltage rises towards V_s, the tube with the slightly lower value of V_s will strike first and the voltage across the tubes will then fall to the maintaining voltage of the conducting tube. Even if more than one tube conducts, the tubes will not pass the same current, so one of them will probably be overloaded.

CASCADED TUBES

If a very stable source of voltage is required, it is common practice to employ a stabiliser tube (V_1 in Fig. 5.3) to provide a stabilised voltage for the operation of the reference tube circuit of V_2. It is essential to ensure that the maintaining voltage of V_1 exceeds the striking voltage of V_2 or the latter tube may not strike. This type of circuit is suitable for use only when the load current is fairly constant. Although it provides better stability against variations of the supply voltage than a circuit employing a single tube, the use of two cascaded tubes does not improve the stability against variations in the load current.

When a cascaded circuit is to be designed, V_2 should first be chosen to provide the desired output voltage. When V_1 has been
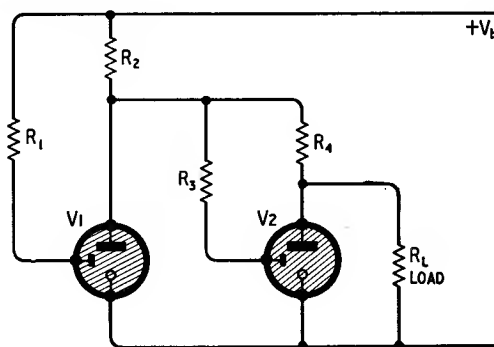
Fig. 5.3. A circuit employing cascaded stabiliser tubes.

chosen, the value of R_4 should be selected so that V_2 will operate at the recommended current. This resistor must normally be a close tolerance component or it will probably be found that an excessive power supply voltage will be required. Finally R_2 is selected using equations 5.7 and 5.8, the reference tube circuit of V_2 being regarded as the load on the stabiliser tube circuit of V_1. R_1 and R_3 are the current limiting resistors for the priming anodes.

MULTI-GAP STABILISER TUBES

Some voltage stabiliser tubes contain more than one discharge gap in a single envelope. In one type of tube, the G.E.C. 'Stabilovolt', the electrodes are cup shaped and are mounted concentrically on an insulating base with the cathode innermost (Fig. 5.4). External
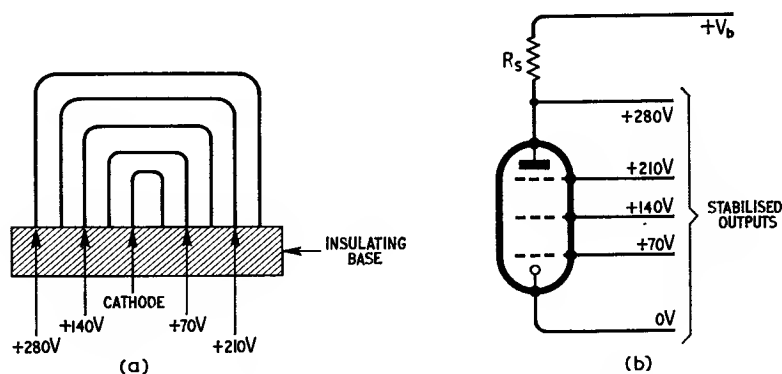
Fig. 5.4. (a) The electrode structure of the Stabilovolt; (b) the Stabilovolt circuit.

connections are taken from each of the five electrodes. Stabilised outputs in multiples of 70 V up to a maximum of 280 V are obtainable from the one tube.

If the first intermediate electrode is earthed, stabilised outputs of -70, $+70$, $+140$ and $+210$ V can be obtained. Two or more of the tubes may be operated in series to produce stabilised voltages at intervals of 70 V up to any reasonable value.

Another type of multi-gap tube, the Telefunken STV500/0, 1, employs four gaps to produce stabilised outputs of 125, 250, 375 and 500 volts. The four gaps are completely independent of one another and need not necessarily be connected in series, since each of the eight electrodes has a separate base pin. Two of the gaps may be used as V_1 of Fig. 5.3 and a third gap as V_2.

CORONA STABILISER TUBES

A corona stabiliser tube contains a thin anode wire in the centre of a cylindrical metal cathode, the envelope being filled with hydrogen gas. Almost the whole of the potential difference applied to the tube is present across the glowing sheath which surrounds the central anode wire; this potential difference is approximately proportional to the gas pressure. Corona tubes can be made with almost any value of the maintaining voltage above a minimum of about 340 V by a suitable choice of gas pressure and electrode diameter. In glass tubes the pressure is kept below atmospheric, but high voltage metal tubes with ceramic insulation are available in which the gas pressure is above atmospheric. The maintaining voltage is dependent on the electrode geometry but not on the nature of the electrode surfaces.

In the region outside the glowing sheath, the voltage drop is approximately proportional to the current flowing. Thus this region acts as a positive resistance and limits the value of the stabilisation factor (see equations 5.1 to 5.5). The voltage drop across this region should therefore be kept as low as possible. The tubes are filled with hydrogen, since this gas has a light and, therefore, mobile positive ion; this enables the voltage drop between the outside of the glowing sheath and the cathode to be kept relatively small. Hence the incremental resistance, R_d, is smaller than if other gases were used. In addition the use of hydrogen enables a greater current range to be attained in the corona discharge mode without the formation of streamers.

Tubes with a higher working voltage can be produced by the use of cathodes of a larger diameter. However, this leads to an

increase in the incremental resistance owing to the greater voltage drop across the region outside the glowing sheath. If the electrode length is increased, the maximum current rating will be increased whilst the incremental resistance will be decreased. The incremental resistance is greater for sudden voltage changes, since the tube takes time to come into thermal equilibrium.

The maximum current rating of a corona tube is set by the danger of a streamer being formed and hence of the tube switching to the glow discharge mode of operation. Maximum currents of 0·3 to 2 mA are typical. Corona discharges from a point are not used for voltage stabilisation, since the small area of such an electrode would result in streamers being formed at currents of a few microamps. The minimum current rating for corona tubes is determined by the need to avoid intermittent switching between the non-conducting and the corona states. Minimum current ratings of between 1 and 30 μA are typical.

Corona tubes are used in the same type of circuit as glow stabiliser tubes and zener diodes (see Fig. 5.1), but owing to the smaller currents and greater voltages, much larger values of resistors are employed. The equations already given for glow stabiliser tubes also apply to corona tube circuits. One important difference, however, is the fact that corona tubes will strike at applied voltages a few per cent above their maintaining voltages. The power supply voltage is normally between 1·2 and 1·5 times the maintaining voltage and therefore no precautions are needed to ensure that a corona tube will strike. Some low voltage corona tubes employ radioactive priming to ensure prompt striking. The operating current is usually set at about the centre of the recommended range.

The stabilisation factor is given by the same equations as those used with glow stabiliser tubes (equations 5.1 and 5.2). The internal resistance of a corona tube is typically 100 kΩ and the series resistor 10 MΩ, so in this typical case:

$$S \simeq \frac{R_s}{R_d} = \frac{10^7}{10^5} = 100$$

As in the case of glow stabiliser tubes, the noise produced by a corona tube increases with decreasing current. It is usually in the range 5 to 500 mV and may be reduced by the use of a parallel capacitor across the tube. Corona tubes do not show the sudden voltage jumps exhibited by glow stabilisers, since they are not affected by minor non-uniformities of the cathode surface.

Corona stabilisers should not be connected in parallel. They may, however, be connected in series to obtain a higher output voltage provided that a capacitor of about 2,000 pF is placed in parallel

with each tube to prevent oscillations occurring. Two corona tubes of different operating voltages may also be used in cascade to obtain a higher stabilisation factor.

Corona stabiliser tubes are used in equipment requiring a fairly high or a high voltage at a low current. They have been widely used in nucleonic equipment for stabilising E.H.T. supplies to scintillation counters, Geiger tubes and proportional counters. They are also used in some instrument work, for example in the power supply circuits for precision cathode ray tubes and in gas chromatography.

Nevertheless glow stabilisers are much more commonly used than corona stabilisers since they can be used for voltage and current ranges which are more commonly required.

THE USE OF COLD CATHODE TUBES IN VALVE STABILISERS

Although voltage stabilisation using thermionic valves is hardly a subject which one would expect to find discussed in a book on cold cathode tubes, a very brief review of this subject is included to show how cold cathode tubes are employed in such circuits.

Voltage stabiliser circuits may be divided into the two main types illustrated by the block diagrams of Fig. 5.5. In the shunt stabiliser
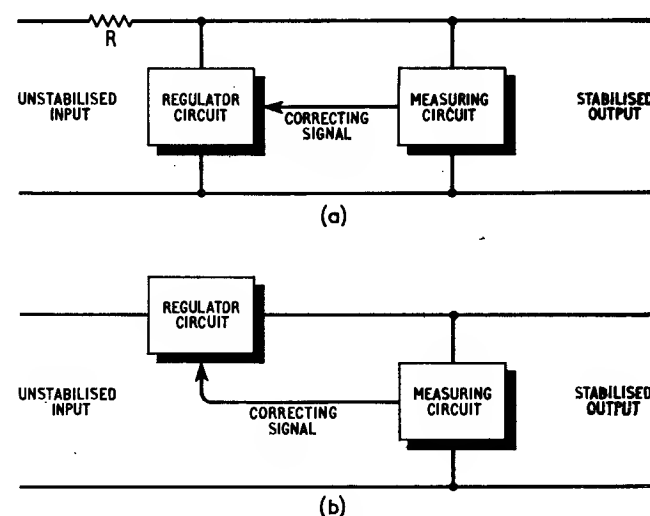
Fig. 5.5. Basic stabiliser circuits.

circuit of Fig. 5.5(a), any decrease in the output voltage is detected by the measuring circuit. This circuit feeds a correcting signal to the regulator circuit so that less current passes through the latter. The reduced voltage drop in the series resistor, R, almost compensates for the initial decrease in the output voltage.

The glow or corona circuit of Fig. 5.1 is a shunt stabiliser in which the tube functions as both the measuring and regulating devices.

In the series circuit of Fig. 5.5(b), any change in the output voltage will be detected by the measuring circuit and the resulting
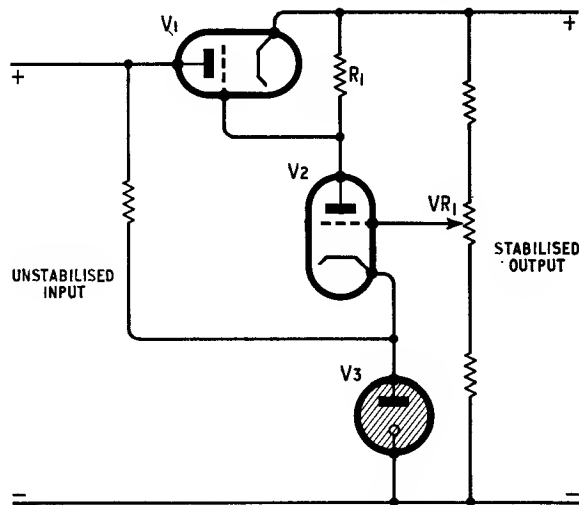
Fig. 5.6. A series stabiliser.

correcting signal is fed to the regulator circuit. The voltage drop across the latter is thus altered in such a way as to almost compensate for the initial change in the output voltage.

A simple series voltage stabiliser may take the form shown in Fig. 5.6. If the output voltage increases, the grid potential of $V2$ rises and the increased anode current passed by this valve results in a greater voltage drop across R_1. Thus the grid of the regulator valve $V1$ becomes more negative and the voltage drop across this tube therefore becomes larger. If the gain provided by $V2$ and $V1$ is high, the output voltage will remain almost constant. In practice a pentode or cascode double triode is used for $V2$ in order to obtain a high gain. Stabilisation factors of about 1,000 can thus be obtained. If the load current changes by 250 mA, the output voltage may change by a small fraction of one per cent. The value of the output voltage can be adjusted by VR_1.
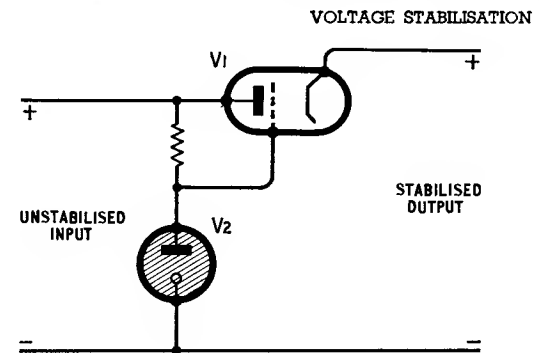
Fig. 5.7. A cathode follower series stabiliser.

In this type of circuit it is essential that the cathode potential of $V2$ should remain constant as the cathode current of this valve changes, since the effective control voltage is that between the grid and the cathode of this valve and not that between the grid and the negative supply line. A cathode resistor cannot therefore be used, since it would provide enough negative feedback to greatly reduce the gain of $V2$ and hence the stabilisation factor. In practice a voltage reference tube, $V3$, is used. Sometimes an additional reference tube is employed in the anode circuit of $V2$ to obtain an increased gain.

Glow stabiliser tubes (or, for higher output voltages, corona stabiliser tubes) may be used in the cathode follower series stabiliser circuit of Fig. 5.7. This type of circuit enables a greater current to be taken from the output than could be obtained by the use of a cold cathode stabiliser tube alone in the simple circuit of Fig. 5.1.

The shunt stabiliser circuit of Fig. 5.8 employs a reference tube $V2$ to keep the cathode potential of the valve $V1$ constant. Thus the
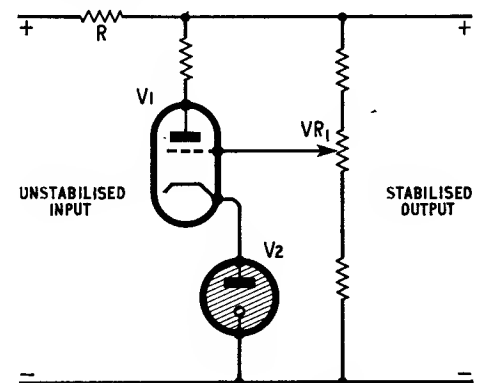
Fig. 5.8. A shunt stabiliser.

effective control potential (that is, the grid to cathode potential of V_1) will vary in the same way as the potential tapped off by the potentiometer VR_1. VR_1 enables the output voltage to be altered.

In general, shunt stabilisers should be avoided where the load current is subject to wide variations, since a large current must pass through the shunt valve and this represents wasted energy.

VOLTAGE STABILISATION USING TRIGGER TUBES

The basic circuit of one type of trigger tube voltage stabiliser is shown in Fig. 5.9. When the mains supply voltage is first connected, the full wave rectified output from the diodes D_1 and D_2 charges the capacitor C via R_1 and D_3. After a few half cycles of the mains supply, the voltage at the junction of R_3 and R_4 becomes equal to the trigger striking voltage of the tube. The tube then strikes and its anode voltage falls to the tube maintaining voltage. The resistor R_2 is fairly small and, therefore, the diode D_3 becomes
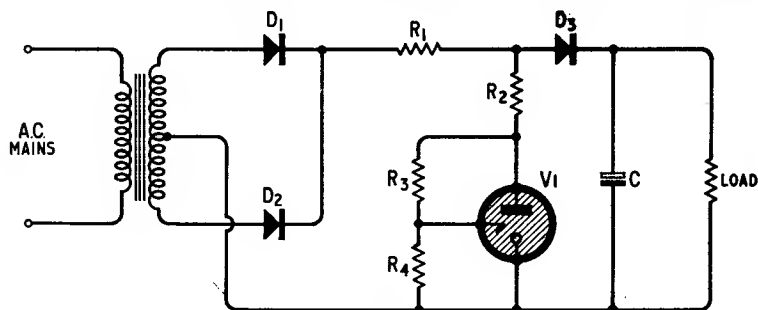
Fig. 5.9. The basic circuit of a trigger tube stabiliser.

reverse biased. During the remainder of the half cycle of the mains supply voltage all of the current passes through the trigger tube instead of passing to the load. During the next half cycle the anode voltage of the trigger tube again increases and any charge which has passed from the capacitor C to the load will be replaced before V_1 ignites. As soon as the potential across C is great enough for the trigger gap to strike, D_3 will be reverse biased and no further charge will pass to C during the half cycle.

If no load is connected across the output of the circuit, virtually all of the current passing through R_1 will pass through the trigger tube except during the initial period when C is charging.

The moment during the half cycle at which the trigger tube fires determines the charge which is passed to the capacitor during that

half cycle. By altering the fraction of the anode voltage which is tapped off by R_3 and R_4, the voltage across C at which the trigger tube will fire is changed. Hence the output voltage across the circuit can be altered.

A trigger tube with a stable close tolerance trigger ignition voltage (such as the Mullard Z806W) is suitable for this type of application. The trigger thermal hysteresis effect may limit the stability obtainable, since a variation of the power supply voltage or of the load resistor will alter the mean current flowing through the trigger tube and hence the tube temperature. Thus the trigger ignition voltage is slightly affected by such changes. However, a stability of the order of 2 per cent can be obtained for mains voltage changes of $+10$ to -15 per cent. The output impedance is lower than that from a normal glow stabiliser circuit.

In the simple type of circuit shown in Fig. 5.9, the output voltage must be greater than the trigger ignition voltage but less than the anode striking voltage of the tube used. More complicated circuits have been designed for larger output voltages and/or currents. In a typical case the circuit in Fig. 5.9 may provide an output in the range 200 to 360 V at currents of about 10 mA. Somewhat higher currents can be obtained with modified circuit values provided that the load resistor is never disconnected, since this would result in the trigger tube current becoming excessive. If the output current is made variable by taking the trigger electrode to a potentiometer in the resistor chain, the output current range will be reduced.

SUGGESTIONS FOR FURTHER READING

CIRCUIT DESIGN

D. M. NEALE, 'Cold Cathode Tube Circuit Design', Chapman and Hall, London (1964).
'Design of Stabilising Circuits', Cerberus sheets 5.07e (Nov. 1963).
'Stabilizer and Reference Tubes', Ericsson Telephones publication B.6201/1 (1963). (Now available from Hivac Ltd.)
M. VOLLENWEIDER, 'Präzisions-Stabilisierungsröhren und ihre Anwendung für die Stabilisierung von Gleichspannungen', *Cerberus Elektronik*, 10 (April 1959).

CORONA TUBES

E. COHEN AND R. O. JENKINS, 'The characteristics and applications of corona stabilizer tubes', *Electron. Eng.*, 32, 383, 11 (1960).
'High Voltage Stabilisation', G.E.C. Application Report No. 16.

TRIGGER TUBE STABILISERS

E. P. T. ATKINSON AND C. F. HILL, 'Voltage stabilization using cold cathode trigger tubes', *Electron. Eng.*, 37, 454, 788 (1965).

6
Cold Cathode Stepping Tubes

Cold cathode decade stepping tubes were first produced about 1950 for the counting of electrical pulses. The use of such tubes enables much simpler counting circuits to be constructed than the ring circuits of Figs. 2.4, 3.10 and 3.11, since only one stepping tube is required in each decade. Coupling from one position to the next takes place automatically in each tube by means of the ions formed in the discharge—no separate coupling components being employed. Circuits using decade stepping tubes are one of the simplest and most widely used types of circuit for medium speed counting. They have been much used for nucleonic and other applications, but their use is not confined to pure counting. They can, for example, be used to route speech signals or to control the time for which a welding current is passed.

Cold cathode stepping tubes consist of a central electrode, normally the anode, surrounded by a large number of other electrodes. The tubes are viewed end-on through the dome of the glass envelope, the state of the count being indicated by the position of an orange-red or a blue glow discharge. In the zero position the glow is vertically above the centre of the tube. Each input pulse causes the discharge to move one position in a clockwise direction until, at the tenth pulse, the glow completes one rotation and returns to the zero position; an output pulse which is produced at this time can be fed to the circuit of a succeeding stepping tube which counts the number of tens. The domed end of each tube is normally placed in a panel mounted escutcheon on which the digits 0 to 9 are marked. The digit to be indicated is the one on the escutcheon which is adjacent to the glow discharge.

Cold cathode stepping tubes are often known as 'Dekatrons', although this name is a registered trade mark of Ericsson Telephones

Ltd. and should not be applied to the tubes of other manufacturers. (Ericsson tubes are now available from the Hivac company.)

CONSTRUCTION

Most decade stepping tubes consist of a central disc shaped anode surrounded by twenty, thirty or forty rod shaped cathodes; the latter often consist of nickel wires. Groups of the cathodes are connected together internally so that the number of external connections to the tube is not excessive.

Ten of the cathodes are known as main or index cathodes. When the glow discharge rests at one of these cathodes, the corresponding digit is indicated. The remaining cathodes are known as transfer or guide electrodes, since they take part in the movement of the discharge from one main cathode to the next main cathode and determine the direction of rotation of the glow.

The transfer cathodes receive a positive bias so that the voltage between the anode and a main cathode is greater than that between the anode and any transfer cathode when the tube is in the quiescent state. The glow discharge will not normally remain at any transfer cathode except during the time the transfer operation is taking place.

DOUBLE PULSE TUBES

The most commonly used type of decade stepping tube is the so called double pulse tube. The symmetrical electrode structure of such a tube is shown in Fig. 6.1. It can be seen that there are ten main cathodes (marked K_0 to K_9), ten first guides and ten second guides. All of the first guides are brought out to a common external connection and all of the second guides also have a single external connection. Adjacent cathodes in the ring are about 2 mm apart.

When the discharge rests at any main cathode, the ions formed will prime the two adjacent guide cathodes; that is, the presence of the ions will reduce the anode to guide striking voltage. The tubes are designed so that the amount of priming to cathodes which are not adjacent to the discharge is as small as possible. In practice the striking voltage of the cathodes adjacent to the discharge is reduced to about 10 V above the maintaining voltage, whereas that of a cathode two places away from the discharge is about 40 V above the maintaining voltage.

The transfer voltage is the potential difference between two cathodes at which the discharge will transfer from the one cathode

G_1 = FIRST GUIDES
G_2 = SECOND GUIDES
K = A MAIN CATHODE
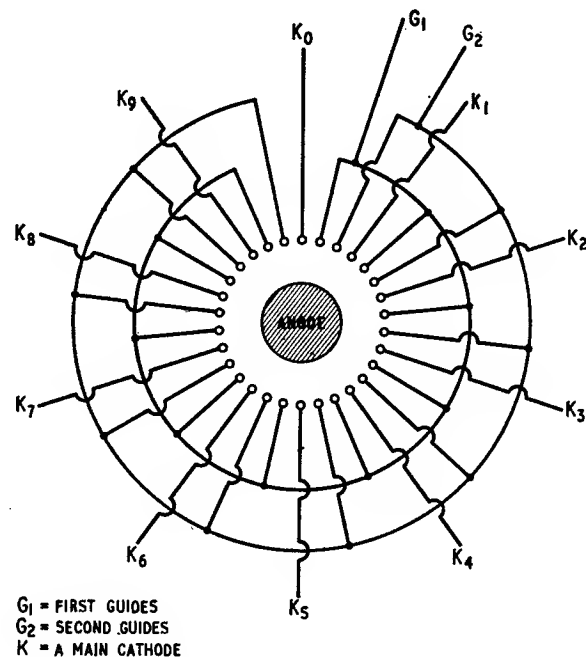
Fig. 6.1. The structure of a double pulse decade tube.

TO POSITIVE GUIDE BIAS

FIRST GUIDES

+ H.T.

R_a

SECOND GUIDES

MAIN CATHODES

R_k

− H.T.

OUTPUT PULSE FOR THE OPERATION
OF THE NEXT DECADE
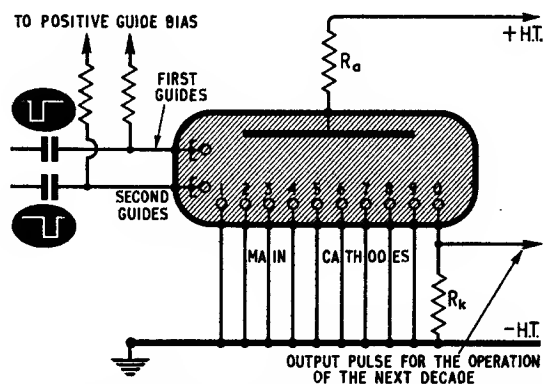
Fig. 6.2. The basic circuit for the operation of a double pulse tube.

to the other owing to ionisation coupling. It can be seen from the previous paragraph that the transfer voltage between adjacent cathodes is about 10 V. Thus when the potential of a cathode adjacent to the glowing cathode falls to 10 V or more below that of the glowing cathode, transfer will take place.

The basic circuit in which double pulse stepping tubes are normally used is shown in Fig. 6.2, the circular electrode structure of the tube being represented as a linear one for convenience. The square brackets by the guide electrodes show that there is more than one first guide and more than one second guide in each tube. Both sets of guides receive a positive bias voltage of about 40 V.

When any main cathode is conducting, the anode voltage falls to the maintaining voltage of the tube (often about 190 V). This is below the striking voltage of any other anode to cathode gap. Thus when one main cathode strikes, no other cathode will conduct.

DOUBLE PULSE COUNTING

In order to cause a tube to register a count, a negative going pulse of perhaps 100 V in amplitude is initially fed to the first guide electrodes. When their potential has fallen to about 10 V below the potential of the glowing main cathode, the discharge will move one position in a clockwise direction to the first guide which is adjacent to this main cathode. No other first guide is sufficiently primed for it to pass an appreciable current. The anode voltage falls with the conducting guide voltage so that the potential between these electrodes remains constant at the maintaining voltage of the gap. This fall of anode voltage results in the discharge at the main cathode being extinguished, since the potential across the anode to main cathode gap is now less than the maintaining voltage. There is no tendency for the discharge to move from the main cathode in an anti-clockwise direction, since the preceding second guide is at a potential equal to the guide bias above the main cathode potential.

A short time before the negative going pulse to the first guides terminates, a similar negative going pulse is applied to the second guides. When the first guides return to their quiescent positive potential, the discharge moves one step in a clockwise direction to the second guide which is being primed by the conducting first guide. None of the other second guides can strike, since they are not sufficiently primed.

At the end of the second guide pulse, these guides return to their quiescent positive bias potential and the glow therefore moves a

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further step in a clockwise direction to the succeeding main cathode which has been primed by the discharge to the second guide. Thus the glow moves in three distinct steps each time a count is registered.

Double pulse tubes derive their name from the two separate successive input pulses which must be applied to the guide electrodes to cause the stepping operation to take place.

The electrode structure of double pulse tubes is symmetrical in each direction and the glow can therefore be made to move in either a clockwise or in an anti-clockwise direction. The direction
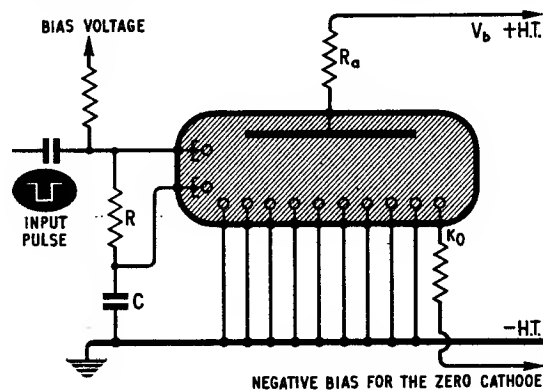
Fig. 6.3. The basic integrator circuit.

of rotation is determined by the order in which the pulses are applied to the two sets of guide electrodes. If the second guides receive their negative going pulse before the first guides, the glow will rotate in an anti-clockwise direction for reasons which should be clear from a consideration of the electrode structure of Fig. 6.1. Anti-clockwise rotation of the glow corresponds to subtraction of the incoming input pulses from the number of counts being indicated.

When the zero cathode (Fig. 6.2) conducts, a positive going output pulse is provided from this cathode; this pulse may be amplified and phase inverted for the operation of a succeeding decade tube which counts the number of tens.

In a practical counting circuit the two separate negative going pulses for the guides must be obtained from a single input pulse. This is most commonly effected by means of a circuit of the type shown in Fig. 6.3. A negative going input pulse is applied directly to the first guides, but the second guides receive it via the integrating circuit. One may regard the capacitor as taking time to charge via the resistor; therefore the pulse does not reach the second guides

as soon as it reaches the first guides. In addition the charge of the capacitor will maintain the second guide potential negative for a time after the first guides have returned to their quiescent bias potential. Thus the integrating circuit effectively delays the pulse to the second guides. Although the circuit has a considerable effect on the pulse shape at the second guides, this is not very important unless the counting speed is high.

A cold cathode stepping tube takes a certain time to register a count. When a pulse is applied to the first guides, there is a short delay before the glow discharge is fully formed. In addition the second guide preceding the previously conducting main cathode takes time to become deionised. If the second guide pulse is applied too early, the discharge may be formed at the second guide preceding the previously conducting main cathode; in this case it will return to the main cathode from which it came at the end of the second guide pulse and no count will be registered. There are similar delays associated with the stepping of the discharge from the second guide to the next main cathode. If an attempt is made to drive the tube at too high a counting rate, faulty counting will occur.

OPERATING SPEED

Many of the double pulse tubes have a maximum recommended operating rate of about 4 kc/s (that is, 4,000 pulses per second). Each of the guide bias pulses should have a duration of not less than 75 μsec. Suitable pulses of a controlled duration may be obtained from a monostable circuit. Faster double pulse tubes are available which can be used for counting at speeds of up to 10 kc/s, 20 kc/s, 50 kc/s or 100 kc/s. They will operate from shorter input pulses. For example, the American 100 kc/s double pulse tubes can operate from pulses which have a duration of 4 μsec.

High speed tubes normally operate at a higher anode current than the 4 kc/s tubes. This enables a lower value of series resistor to be used and hence reduces the anode circuit time constant. However, the conditions of operation are very critical at high speeds; it may be necessary to select the anode current for each individual tube and to use input pulses of accurately defined amplitude and duration.

A helium-neon gas filling is employed in most of the 4 kc/s double pulse tubes. As the pressure of the gas is decreased, the glow expands and the concentration of the ions increases at neighbouring cathodes. The pressure is selected so that the cathode adjacent to the glowing cathode is strongly primed, whilst the amount of

Fig. 6.4. A valve coupling circuit for Dekatrons.

V_1, V_3	Counters	GS10C	GS12D
R_1	10 kΩ	22 kΩ	22 kΩ
R_2	820 kΩ	680 kΩ	910 kΩ
R_3	150 kΩ	150 kΩ	270 kΩ
E	+18 V	+36 V	+36 V

priming to the other cathodes is as small as possible. Stepping tubes do not employ Penning mixtures, since this would result in an inadequate difference between the amount of priming at a cathode adjacent to the discharge and that at other cathodes.

In some tubes, known as counters, only the zero main cathode is brought out to a separate base pin, but in the so called 'selector' tubes each main cathode has a separate external connection. Selector tubes can be used to obtain an output from any desired cathode.

PRACTICAL CIRCUIT

A circuit designed by Ericsson Telephones Ltd. for coupling their 4 kc/s Dekatrons is shown in Fig. 6.4. The zero cathode resistors of the decade tubes are returned to a —20 V line, since output pulses of larger amplitude can thus be obtained than if these cathodes were returned directly to earth. It is not possible to obtain a large output pulse merely by using a large value of cathode resistor, since if the output cathode becomes too positive, faulty counting will occur. The —20 V supply also serves the purpose of biasing the coupling valve to cut off.

When the discharge reaches the zero cathode of the first decade tube, the voltage developed across the cathode resistor will cause the coupling valve to conduct. The resulting fall of anode voltage of this valve provides the necessary negative going pulse for the operation of the second decade tube, V_3.

The output pulses from V_3 may be employed to drive a similar valve coupling circuit. Any number of similar succeeding decade circuits may be added so that it is possible to count up to any desired number. The first decade tube is often driven by a monostable circuit.

RESET

The cathodes of the stepping tubes other than the zero cathodes are returned to the reset line. The latter is connected to earth via a resistor which is normally shorted out by a switch or by relay contacts. During the resetting operation the switch or contacts are opened and the current from the counting tube cathodes flows through the resistor to earth. The potential of all of the cathodes except the zero cathodes is thereby raised so that the glow moves to the zero cathode in each tube. The value of the resistor used should
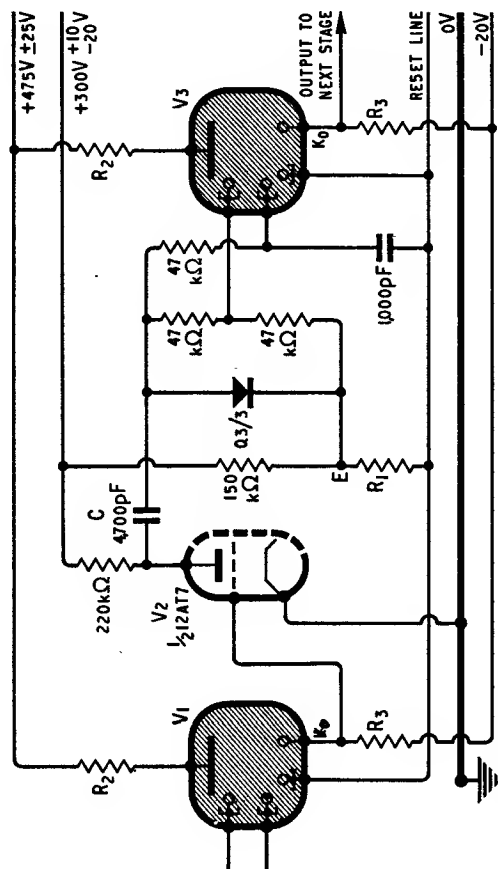
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be such that the potential of the reset line increases by about 100 V during the resetting operation. The greater the number of decades, the smaller the value of the reset resistor required.

If a selector tube with a resistor in each main cathode circuit is employed, the average cathode current will be less than in a similar circuit using a counter tube in which nine of the cathodes are directly earthed. When a selector tube is employed, a 680 kΩ anode resistor is therefore recommended so that the total resistance in series with the tube is kept at about the optimum value. In addition a higher guide bias is recommended for selector tubes used with cathode resistors.

SINGLE PULSE TUBE

A somewhat different type of tube is the single pulse Dekatron, type GC10D. This has forty cathodes around a single anode, three guide electrodes being placed between each two main cathodes.

This tube has the advantage that it can be operated by a single pulse and will function at frequencies up to 20 kc/s. The negative going input pulses are applied via a parallel resistor-capacitor network to the first guide electrodes and directly to the second guides. When the first guide draws current at the beginning of the input pulse, its potential increases owing to the flow of current through the feed resistor. Thus the discharge passes automatically to the second guide. At the end of the input pulse the first two guides return to their positive bias potential and the discharge moves to the third guide which is returned to earth via a parallel resistor-capacitor network. The flow of current through this resistor raises the potential of the third guide and causes the discharge to move to the succeeding main cathode.

Although four separate glow transfers occur each time a count is registered by a single pulse tube, the maximum counting speed is greater than that of many of the double pulse tubes. The single pulse tube emits a blue glow in operation, since it contains a hydrogen-helium gas mixture. It is not normally possible for the tube to be used for reverse counting.

ASYMMETRICAL TUBES

Double pulse tubes are symmetrical in their structure and can be used to count in either direction. However, two guide electrodes are required between each two main cathodes to determine the

direction of counting. Other types of tube have been designed in which the direction of counting is determined by the asymmetrical electrode structure of either the main cathodes or the transfer cathodes or both. Only one set of guide electrodes is required in such tubes.

When a negative going pulse is applied to all of the guide electrodes of such a tube, the glow discharge moves to the guide which is one position in the clockwise direction from the previously glowing main cathode. At the end of the pulse the guide electrodes return to their positive bias potential and the discharge steps to the next main cathode.

When the discharge is established at any cathode, a narrow adjacent part of the succeeding cathode is primed by the ions present. On transfer of the glow, the discharge moves first to the narrow part of the succeeding cathode and then automatically moves to the wider part which has a sufficient area for the value of the ionisation coefficient, η, to be a maximum. The previously glowing cathode is then no longer primed to any great extent and the discharge will not be able to move back to it. This process may be assisted by a parallel resistor-capacitor network in each cathode circuit. The capacitor charges whilst the cathode to which it is connected is conducting. The cathode is thus held at a positive potential by the charged capacitor for a short time after the glow has moved to the next cathode. This potential opposes any tendency of the discharge to move back to the previously conducting cathode.

A number of asymmetrical tubes have been manufactured. The Cerberus DZ10 can count at speeds of up to 3 kc/s, the S.T.C. G10/241E 'Nomotron' tube up to 20 kc/s and the Elesta EZ10B (which contains hydrogen) up to 1 Mc/s. Most asymmetrical tubes are, however, no longer recommended for use in newly designed equipment, since transistor counting circuits are becoming increasingly competitive as the prices of high speed semiconductor devices fall. This type of tube will not therefore be discussed further. There is no means of reversing the direction of rotation of the glow and therefore asymmetrical tubes cannot be used for reverse counting (subtraction).

OTHER TYPES OF STEPPING TUBE

Various other types of cold cathode stepping tube have been designed. Inverse tubes employ a central cathode surrounded by thirty wire anodes. The principle of operation is similar to that of

conventional double pulse tubes except that successive positive going double pulses are applied to the first and second guide anodes instead of the negative going pulses required for the operation of conventional double pulse tubes. Inverse tubes are reported to have characteristics which remain very constant during life and they are capable of operating digital indicator tubes (see Chapter 7) directly; conventional stepping tubes require ten valve, trigger tube or transistor amplifier stages per decade if digital indicator tubes are to be employed.

Inverse tubes with only twenty guide anodes have been constructed. The direction of rotation is determined by the polarity of an applied magnetic field.

The Elesta ECT100 is a reversible counting tube capable of counting at frequencies of up to 1 Mc/s. It employs one transfer electrode between each two main cathodes. Alternate main cathodes are connected together in two groups of five each, as are alternate transfer electrodes. Both the main cathodes and the transfer electrodes receive pulses from a bistable circuit, the potential of one main cathode rising as that of the succeeding main cathode falls. The direction of counting is controlled by the polarity of the guide pulses relative to the main cathode pulses.

ANODE CIRCUIT DESIGN

The data sheets for decade stepping tubes specify a maximum and a minimum value of the anode current. If the maximum value is exceeded, the life of the tube is likely to be much reduced by excessive sputtering, whilst at anode currents below the minimum recommended value, the amount of priming will be so small that the transfer of the glow will not take place very easily. Generally about half of the cathode which is glowing should be covered by the discharge.

Equations 1.5 and 1.6 of Chapter 1 may be used to select an appropriate value of the anode resistor. If one or more of the cathodes are connected directly to the negative supply line, the value of R_{min} to be substituted in equation 1.5 will be the value of the anode resistor. The value of R_{max} to be used in equation 1.6 will be the sum of the values of the anode resistor and of the highest value of cathode resistor employed. A single value of V_m is often quoted in data sheets, in which case $V_{m(max)}$ and $V_{m(min)}$ may be taken as being equal.

There is normally no upper limit on the value of the H.T. supply voltage used provided that a suitable anode resistor is

employed to limit the current flowing. However, a minimum value of the supply voltage is quoted by the tube manufacturers in their data sheets. At values of the power supply voltage below this minimum the tubes may fail to strike. The striking voltage is normally much larger than the maintaining voltage. If the applied voltage is only slightly above the minimum recommended value, there may be a considerable delay (occasionally over a minute) in the striking of a tube, especially if it is being operated in total darkness. No form of priming is included in stepping tubes, since a discharge is always present at some point in each tube which is operating and this provides some ions to all parts of the tube. Striking will not therefore occur until natural radiation gives rise to an electron which is able to initiate a discharge.

The design of stepping tube circuits is fairly critical and it is generally advisable to employ circuits which have been designed and thoroughly tested by the manufacturers of the tube concerned unless there is some special reason for designing a new circuit.

It is good practice to solder the anode resistor of a stepping tube directly to the anode connection on the tube base. Indeed, this is essential for those tubes which are used for high speed counting in order to minimise stray capacitance. Any stray capacitance from the anode to earth will limit the rate of rise of the anode potential at the end of the guide pulses and may result in the anode to cathode potential falling below the maintaining voltage of the tube. In this case the discharge will be extinguished and re-striking may occur at any position in the tube.

The life of stepping tubes is limited by the sputtering of the cathode material on to adjacent cathodes. If the glow discharge circulates around the tube fairly frequently, any sputtered material will be removed from the cathodes and the tubes will have a long life. If, however, the discharge remains at one cathode for some weeks, the material sputtered on to the adjacent cathodes makes transfer of the glow difficult. Such tubes cannot operate at very high speeds, but their performance can be improved by allowing the discharge to circulate for some time. Reverse current should never be allowed to flow through a stepping tube.

Many tubes will operate at speeds considerably in excess of the maximum speed quoted in the manufacturer's data sheet. Some tubes will operate at over five times the maximum quoted operating speed, but close tolerance components and input pulses of defined amplitude and duration are then needed in addition to a stabilised power supply. Although some manufacturers appear to be quite conservative in their ratings, optimum reliability cannot be expected at speeds much in excess of the recommended maximum frequencies.

In general it is not advisable to try to drive a tube at the absolute maximum speed of which it is capable, especially if the tube will be allowed to age to any great extent.

If the maximum operating speed is required, it is worth while making some estimate of the safety margin available by altering the anode supply voltage or the anode resistor as the tube is counting at high speed. Care must be taken to ensure that the anode current does not exceed the maximum recommended value in these tests. If the circuit operates at a certain speed over an appreciable range of anode current, it will probably be fairly reliable when operated at this speed at the centre of this anode current range. Reliability tests may be carried out by varying the pulse amplitude and duration.

OTHER SCALES OF COUNTING

Most stepping tubes are designed for scale of ten counting. That is, one output pulse is produced by the circuit for each ten input pulses applied to it. However, double pulse tubes with 36 cathodes in the ring are available for counting in a scale of twelve. They are useful for registering pence when the succeeding tube is used to count the shillings.

A scale of five circuit can be made using a decade tube by returning the cathodes zero and five to the -20 V negative line through a common resistor. An output pulse is then obtained whenever either of these cathodes pass a current. This occurs twice per rotation of the glow and an output pulse is therefore obtained for each five pulses applied to the circuit. However, the visual indication will not be in a scale of five. Similarly if alternate cathodes in a decade tube are connected to a common resistor, an output pulse may be taken from across this resistor for each two applied input pulses. Scale of twelve tubes may be used in a similar circuit to divide the incoming pulse frequency by a factor of 2, 3, 4 or 6.

SUGGESTIONS FOR FURTHER READING

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7
Indicator Tubes

The use of a miniature neon diode for indicating when the potential between two points in a circuit exceeds the striking voltage of the diode has already been mentioned in Chapter 2. The present chapter describes the various types of tube which have been developed especially for indicating the state of the count in a counting circuit or for displaying some other information. However, cold cathode tubes are not the only means by which electrical signals can be converted into a visible display; various types of optical projection indicators are commonly used, whilst electro-luminescent display panels are also available. The process by which information in the form of electrical signals is converted into a visual display is known as readout.

NUMERICAL AND CHARACTER INDICATOR TUBES

Cold cathode tubes which employ cathodes in the shape of the digits (or other characters) to be indicated are one of the most commonly used devices for providing a visual display of information. In digital indicator tubes each cathode is in the shape of one of the ten digits, only one of these cathodes conducting at any one time. The conducting cathode is surrounded by an orange-red glow which stands out clearly in the form of the digit. Such tubes are often known by the registered trade marks allocated to them by the manufacturers; for example, 'Nixie' tubes are manufactured by the Burroughs Corporation, 'Digitron' and 'Numicator' by the Hivac Company and 'Nodistron' by Standard Telephones and Cables Ltd.

The cathodes of a digital indicator tube are stacked closely behind one another in the tube. The width of the cathode glow is

considerably greater than that of the cathode itself and therefore the glow is not obscured to any great extent by any of the other cathodes which may be in front of it. The anode is in the Faraday dark space—no positive column being present. The Crookes dark space is not normally visible. A number of digital indicator tubes may be placed in a line so that a number consisting of any number of digits may be indicated.

The cathodes are surrounded by an anode in the form of wire mesh. This type of anode prevents an excessive amount of sputtered material from being deposited on the glass envelope of the tube where it would reduce the readability of the displayed digit.

Some types of indicator tube are viewed from the side, whilst others are viewed through the domed end of the tube. End viewing tubes require less panel space than side viewing tubes, whilst side viewing tubes occupy less depth behind the front panel of the instrument. Large cathodes can be accommodated more easily in a side viewing tube.

ANODE CURRENT

The tube manufacturers quote maximum and minimum values of the anode current for each type of tube. If the current is too low, the cathodes will not be completely covered by the glow and the display will be defective. An excessive anode current will lead to a reduced life. The equations 1.5 and 1.6 of Chapter 1 may be used when selecting an anode resistor for a digital indicator tube.

In some tubes it is advisable to employ a smaller current when a cathode of relatively small area is conducting than when a larger cathode is being used. This may be accomplished by including an additional compensating resistor in the circuits of those cathodes which have a small area, e.g. those which indicate the digits 1 and 7. Some tubes have been designed, however, so that the area of each of the cathodes is approximately equal, the digits 1 and 7 being made of somewhat wider metal than the other digits. Compensating cathode resistors should not be used with such tubes.

PRE-BIAS

The current passing to the cathodes of a numerical indicator tube which are not conducting at any time must be kept below the level at which they would be surrounded by an appreciable amount of glow or the display will not be clear. Unused cathodes may, for

example, be left unconnected, but this is not possible in most circuits. In general the cathodes not being used at any instant are biased positively with respect to the conducting cathode by a potential known as the 'pre-bias' voltage.

The current passed by a non-glowing cathode varies according to the pre-bias voltage and the distance of the cathode from the conducting cathode. The effect of the pre-bias may be shown by the
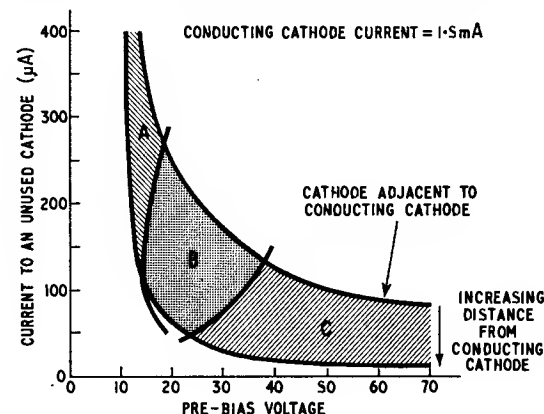
Fig. 7.1. A diagram showing the effect of the pre-bias voltage on a numerical indicator tube display.

type of diagram of Fig. 7.1. The unused cathodes pass such a high current in the region marked A in Fig. 7.1 that the resulting glow more or less completely obscures the desired glow from the conducting cathode. In the region B it is not especially easy to read the information being presented owing to the amount of background light being emitted. Tubes should always be operated in the region C where a clear display is provided, possibly with a slight background haze.

In some tubes a little mercury vapour is added to the gas filling. This gives a considerable improvement in the life of the tube, but produces a slight blue glow. A red filter is usually placed on the glass envelope of such tubes so that the blue glow does not interfere with the clarity of the display.

CIRCUITS

A full discussion of numerical indicator tube circuitry lies outside the scope of this book, since it would first be necessary to discuss
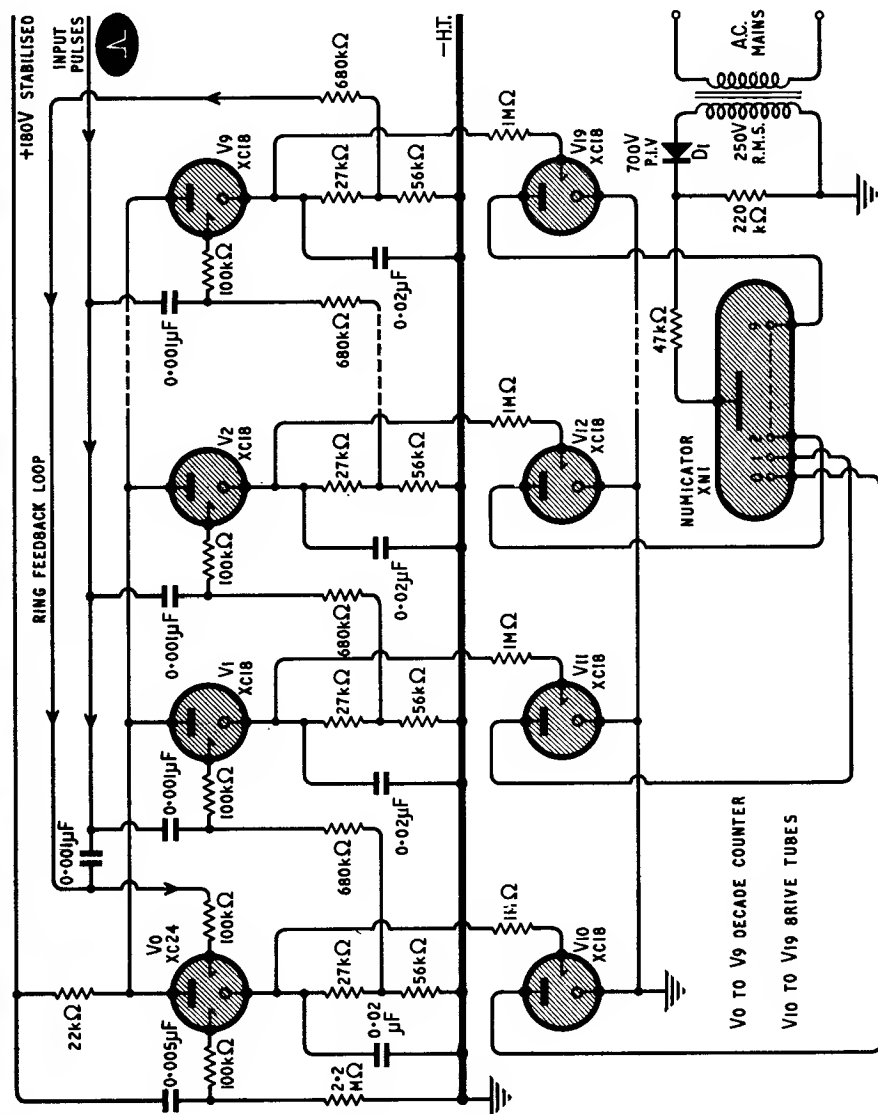
Fig. 7.2. A circuit providing digital readout from a trigger tube ring circuit.

counting circuitry at some considerable length. However, the way in which numerical indicator tubes can be used to provide readout from cold cathode tube counting circuits will be shown.

The circuit of Fig. 7.2 shows how a trigger tube ring counter may be used with trigger tube amplifying stages to drive a numerical indicator tube. This circuit was first published by R. S. Sidorowicz in *Electron. Eng.*, **33**, 296 (May 1961). The first tube of the ring circuit, V_0, is an XC24 with twin trigger electrodes. The one trigger is used for igniting the tube when the circuit is first switched on so that a count of zero is indicated. The pulse from the H.T. line travels through the 0·005 μF capacitor and ignites the tube. The remainder of the ring circuit (V_0 to V_9) is similar to that of Fig. 3.10 except that tapped cathode resistors are employed.

The positive cathode potential of a conducting tube in the ring circuit is used to switch the corresponding trigger drive tube (V_{10} to V_{19}) to the conducting state. A current passes from the appropriate indicator tube cathode to the anode of the drive tube which has been triggered. The indicator and drive tube circuits are fed from a rectified but unsmoothed supply so that a conducting trigger tube is automatically extinguished during the non-conducting periods of the rectifier diode. If a source of steady potential were used as a power supply for these tubes, a trigger drive tube would not be extinguished if the state of the count were altered. In the circuit shown two different digits cannot be shown simultaneously for a period exceeding one half cycle of the mains supply voltage. The maximum counting speed is about 250 pulses per second.

Other circuits have been designed for coupling a trigger tube ring circuit to a digital indicator tube which do not require the ten drive tubes. The anode of each trigger tube in the ring is connected to the corresponding cathode of the indicator tube.

The Ericsson circuit of Fig. 7.3 shows how GTE120Y miniature trigger tubes may be used to couple a decade stepping tube to a digital indicator tube. The display provided by the indicator tube is much easier to read than that provided by the stepping tube and this reduces the possibility of human errors.

The current flowing through one of the stepping tube cathode resistors produces a positive voltage of about 12 V which is used to trigger one of the ten trigger tube amplifier stages. The anode voltage of the conducting trigger tube falls so that the corresponding cathode of the indicator tube conducts. The indicator tube and the trigger tubes are supplied with power from an unsmoothed half wave rectified supply and therefore the current passing through them falls to zero at the end of each half cycle. One of the trigger tubes conducts in each alternate half cycle of the supply voltage.

Similar circuits using valves and transistors instead of trigger tubes can be constructed. A special type of decade tube employing ten additional anodes between the main anode and the ring of cathodes is available; it will drive a numerical indicator tube directly without any intermediate amplifying devices.

If digital indicator tubes are to be used to provide readout from decade circuits employing valve or transistor binary stages, some method must be employed for converting the binary readout into a form which will be suitable for feeding to the ten cathodes of the indicator tube. A matrix of diodes may be used for this purpose.

CHARACTER INDICATING TUBES

Side and end viewing tubes for indicating plus and minus signs are available. They may, for example, be used in conjunction with digital indicator tubes in digital voltmeters to display not only the voltage being measured, but also the polarity of this voltage.

Tubes which indicate certain fractions such as $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ can be produced, but decimal displays are much more common. Tubes for displaying the letters of the alphabet are manufactured, but it is difficult to place all 26 letters in a single tube. Other types of tube are available for indicating the monetary signs of various countries, whilst yet others indicate mathematical or electrical symbols. Tubes for displaying any reasonably small characters can be made.

Tubes which display large digits can be made for viewing from a large distance. They pass a larger current than the smaller tubes.

An alpha-numeric tube which can display any digit or letter is available from the Burroughs Corporation. This tube consists of thirteen rod shaped electrodes arranged in such a pattern that when suitable combinations of them glow, the desired symbols are indicated. It is not always easy to arrange for the correct combinations of the electrodes to glow when a pulse arrives from a switching circuit.

Some types of indicator tube can be operated from an a.c. supply. The use of an unsmoothed half wave rectified supply will increase the life of any numerical indicator tube by a considerable amount at the expense of a slight reduction in the brilliance of the display.

POINT INDICATOR TUBES

Point or position indicator tubes are used to indicate a digit by means of the same type of display as that used in stepping tubes.
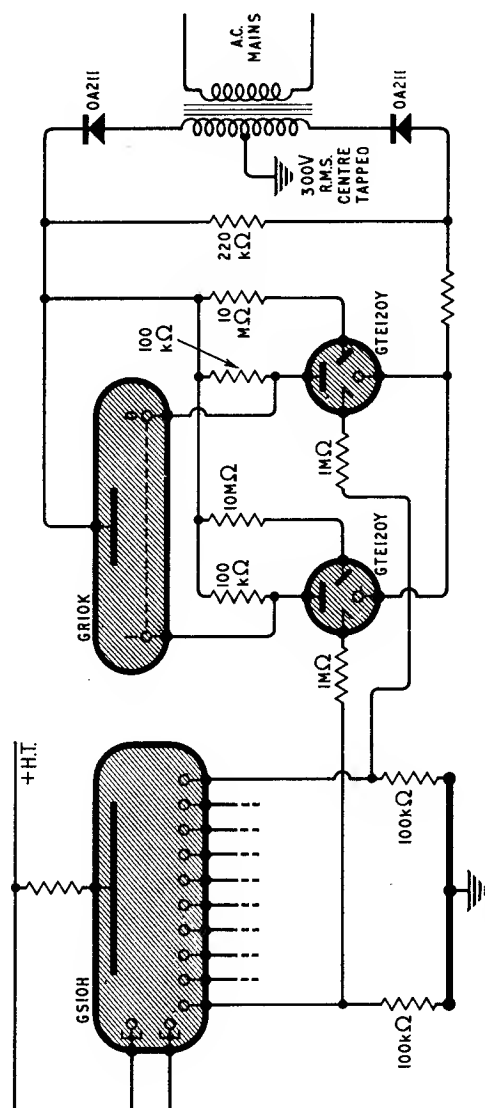
Fig. 7.3. The use of trigger tube amplifier stages to drive a numerical indicator tube from a decade tube circuit.

The construction of point indicator tubes is very similar to that of stepping tubes, but only ten cathodes are present around a central anode. Although such tubes do not provide digital indication, they may be used to obtain readout from valve decades which are followed by slower but simpler stepping tube decades. The form of readout is then the same in all decades.

READOUT FROM TRANSISTOR CIRCUITS

Transistor counting and logic circuits are very widely used, but they have the disadvantage that, unlike cold cathode tubes, they provide no visible indication as to whether they are in the conducting or non-conducting state. The output voltages provided by transistor circuits are normally quite small and it is therefore not generally possible to use these potentials to operate neon indicator tubes. It is possible to use the outputs from a transistor scale of ten counting circuit to operate a numerical indicator tube, but ten amplifying stages are required. Certain cold cathode indicator tubes have, however, been designed so that they can provide readout from transistor circuits without the use of any intermediate amplifier stages.

THE DIGITUBE

The TG122 'Digitube', which is manufactured by the Fujitsu Company of Japan, contains a single anode and two cathodes. One of these cathodes is hidden from the viewer so that a glow is seen only when the other cathode is conducting. If a cathode becomes 5 V negative with respect to the other cathode, this is sufficient to cause transference of the glow. In practice each cathode may be connected to one collector of a binary transistor circuit, the anode being connected via a suitable current limiting resistor to a source of voltage at about 200 V; the tube glows when the binary is in one of its two stable states.

THE HIVAC CIRCUIT

The circuit of Fig. 7.4 has been designed by the Hivac Company for their transistor logic circuit indicators. A current of a few microamps flows through the 10 MΩ resistor whatever the state of the transistor logic circuit. Although this current is too small to
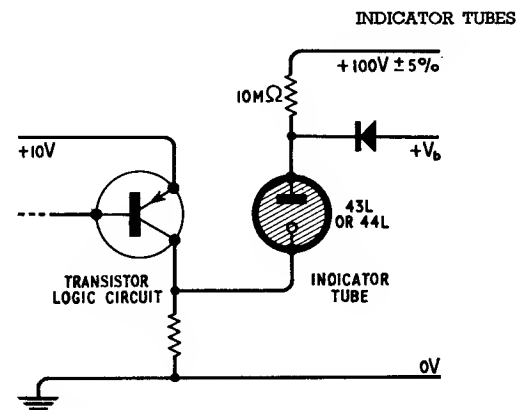
Fig. 7.4. Neon readout from a low voltage transistor circuit. V_b should be 64 $\pm$ 1 volts for the Hivac 43L tube or 68 $\pm$ 1 volts for the 44L tube.

produce a visible glow in normal ambient lighting, it provides enough ions to keep the tube in the conducting state.

When the transistor is not conducting, the collector will be at earth potential. The value of V_b exceeds the tube maintaining voltage; an appreciable current therefore flows through the semiconductor diode and through the tube so that the latter glows. When the transistor is conducting, however, the potential of its collector will be almost +10 V. The anode potential of the tube is, therefore (V_m + 10) volts where V_m is the tube maintaining voltage. As the value of V_b is less than (V_m + 10), the semiconductor diode is reverse biased. Only the current from the 100 V supply now flows through the tube.

The indicator tube will, therefore, glow only when the transistor is non-conducting if the following condition is satisfied with an adequate safety margin:

$$(V_m + 10) > V_b > V_m$$

The Hivac 43L transistor indicator tube (with a lens at its end) has a maintaining voltage of 58 to 62 V, whilst that of the 44L tube is 62–66 V. Thus a slightly higher value of V_b should be used with the latter tube.

CLOCK FACE TUBES

The clock face tubes provide digital indication, but the ten digits are positioned around the tube like the numbers on the face of a clock. When the tube is operating, a glow discharge shines through

one of ten holes in the anode, each hole being in the shape of one digit.

The main anode to cathode gaps are operated from the rectified mains supply voltage. The input voltages are applied to ten trigger electrodes and determine which of the gaps fire first as the supply voltage rises in a half cycle of the mains frequency. Once one gap has fired, no other gap can do so owing to the circuit conditions.

The display provided by a clock face tube can be quite bright, since the control circuit does not supply power to the main discharge. In addition the trigger voltage required to fire a gap need be only about 5 V different from that of the other trigger potentials; this type of tube can therefore be readily operated from transistor circuits without the use of any amplifying devices. Clock face tubes can also be used as counting elements at moderate frequencies.

ANALOGUE INDICATOR TUBES

Up to the present time cold cathode indicator tubes have been used almost exclusively for displaying characters and as 'on/off' indicators but not as devices which can provide an analogue display of the magnitude of a continuously variable quantity. However, an interesting type of cold cathode diode has been developed by the Mullard Company which extends the range of cold cathode tubes into the analogue field. This diode contains a long thin glass tube, the length of the glowing portion being approximately proportional to the current flowing through the tube. Tubes of this type of length between 1 and 8 in. have been made.

The analogue readout tube has the advantage that it can be controlled by the relatively low potentials produced at the output of transistor circuits. However, this type of tube is not suitable when accurate measurements are to be made, since the accuracy with which the length of the glowing column is proportional to the current flowing is limited to about ±5 per cent. Such tubes may, for example, be used in car instrument panels to indicate speed of travel, etc.

SUGGESTIONS FOR FURTHER READING

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N. MCLOUGHLIN, D. REANEY AND A. W. TURNER, 'The Digitron', *Electron. Eng.*, 32, 385, 140 (1960).
'Digitron Display Tubes', Ericsson publication B.6207/2.
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8
Tubes for Detecting Nuclear Radiation

When alpha, beta or gamma radiation passes through matter, the energy of the radiation is used in the formation of ions and excited atoms. If the ions are formed in a gas, they may be collected in the form of a pulse of current which can be amplified and detected. Cold cathode gas filled tubes are one of the most commonly used forms of radiation detector.

The energy of an alpha particle is quickly converted into ions and excited atoms owing to the electrostatic interactions which occur between the particle and the material through which it is passing. A typical alpha particle will travel a few centimetres through air at normal pressure before it loses its kinetic energy. Beta particles, however, can travel through a much greater thickness of material, but they do not produce so many ions per unit length of their path. X and gamma rays on the other hand are still more penetrating; photons of these particular types do not gradually lose their energy, but are absorbed in what are basically single interactions.

CLASSIFICATION OF GAS FILLED DETECTORS

In this section the behaviour of a gas filled coaxial electrode system with a central wire anode will be considered. As the voltage applied to the electrodes is increased from zero, the ions formed by a particle of nuclear radiation move more quickly towards the electrodes and therefore there is a greater probability that an ion will reach an electrode before it meets a particle of the opposite charge. Thus the curve of Fig. 8.1 rises initially in region I with the applied voltage.

Fig. 8.1. The variation of pulse size with applied voltage.

IONISATION CHAMBERS

In region II of Fig. 8.1, virtually all of the ions reach the electrodes. Any further increase of the applied potential therefore has little effect on the current flowing. This region is known as the saturation region.

An alpha particle gives rise to more ions than a beta particle, since much of the energy of the latter is lost when it hits the wall of the tube after travelling through the gas. Therefore the curve for an alpha particle in Fig. 8.1 lies above that for a beta particle.

The so called 'ionisation chamber detectors' operate in region II of Fig. 8.1 where the gas amplification is zero (i.e. $\eta = 0$). These detectors commonly take the form of portable monitors which are

Fig. 8.2. The basic circuit for a radiation detector tube.

used to measure the gamma (or beta and gamma) field in the vicinity of the instrument. The current passing between two planar electrodes is amplified and displayed on a meter as a dose rate reading.

If individual particles are to be counted, the type of circuit shown in Fig. 8.2 may be employed. Each time ions are formed in the tube, a small current passes through it and produces a pulse across the anode load resistor. This pulse may be amplified and counted. Alpha particles produce pulses of the order of one millivolt in a pulse ionisation chamber and can be counted without too much difficulty. However, beta particles produce pulses of only a few microvolts and a really good amplifier is needed to count them. Ionisation chambers which count each individual pulse are not often used, since it is generally preferable to allow some gas amplification to occur.

PROPORTIONAL COUNTERS

If the potential applied to the tube is increased to that corresponding to region III of Fig. 8.1, gas amplification occurs. This region is

known as the proportional region, since the output pulse amplitude from a tube operating in this region (used in the circuit of Fig. 8.2) is proportional to the number of ions formed in the gas by the individual particles of radiation.

Proportional counters are widely used for accurate radioisotope measurements. Argon is often used as the gas filling for alpha counting at a gas amplification of about 100, but methane may be used for beta counting. A greater voltage is applied for beta counting so that the gas amplification factor is high enough for output pulses of about 1 mV to be obtained. Some proportional counter tubes are sealed whereas others employ a gas flow system. The gas pressure is often about one atmosphere.

The electric field strength is very much greater near to the anode wire than elsewhere and, therefore, all of the gas amplification occurs near to this wire. The gas amplification factor is, therefore, the same for ions formed in any part of the tube other than in a very small volume immediately surrounding the anode wire.

In proportional counters it is necessary to prevent a continuous discharge from occurring. The quantity $e^{\eta V}$ must therefore be less than $1/\gamma$ (see Chapter 1). On the other hand $e^{\eta V}$ must not be too small or the gas amplification factor will be low. The quantity γ must therefore be reduced to the minimum possible value by a suitable choice of the cathode material and of the gas filling.

Region IV of Fig. 8.1 is of little importance. However, Geiger-Müller tubes which operate in region V, are the most commonly used form of nuclear radiation detector. A further increase of the applied potential into region VI results in spurious pulses and finally a continuous discharge being formed.

GEIGER-MÜLLER TUBES

When ions are formed in a Geiger-Müller tube, gas amplification occurs and numerous photons are produced. These photons can release electrons from molecules of the gas so that the discharge becomes momentarily self sustaining. However, the sheath of positive ions formed around the anode wire in the discharge moves relatively slowly towards the cathode; this sheath acts as a virtual anode which reduces the potential gradient in the vicinity of the anode wire for a short time after each pulse has passed. The ionisation coefficient, η, and the gas amplification are thus reduced until the discharge ceases. The tube is insensitive to further incident particles until the positive ions have moved some distance towards the cathode; this period is known as the dead time of the tube.

For a period after the dead time the amplitude of the output pulses is less than their normal value; this period is known as the recovery time. The output pulses do not have their full amplitude until the positive ions formed in the previous pulse have reached the cathode. These effects limit the maximum counting speed of a Geiger tube to less than one thousand pulses per second. Proportional counters can operate at much higher speeds.

Any electron which is capable of initiating a discharge in a Geiger tube will cause the discharge to spread along the whole length of the anode wire. Gas amplification ceases only when an adequate positive space charge has been built up around the anode wire. Thus the output pulse amplitude is independent of the energy or of the type of incident radiation.

The gas amplification factor in a Geiger tube is much greater than that in the other two types of gas filled detector and the output pulses are therefore correspondingly larger. A Geiger tube used in the circuit of Fig. 8.2 will provide output pulses of about 1 to 10 V. This is great enough to operate most types of counting equipment directly without the use of any intermediate amplifier. Thus Geiger counting equipment is generally simpler than that used with other forms of detector.

The gas pressure in Geiger tubes is much less than atmospheric. Whilst this enables relatively low voltages to be used, it normally necessitates sealing the tube. Gamma radiation can pass through the walls of a Geiger tube, but a thin window of mica or aluminium is needed if beta particles are to be detected. Geiger tubes with very thin mica windows can be used for alpha particle detection, although other forms of detector are normally preferred for this type of radiation. Thin mica windows can be sealed into the end of a tube with glass. The mica window is very delicate and has a concave external surface owing to the air pressure being greater than that of the gas filling.

The efficiency of Geiger tubes for detecting beta particles which pass through the window and enter the tube is almost 100 per cent. The tubes are also very efficient at detecting alpha particles which pass into the gas. However, the efficiency of any type of Geiger tube for gamma radiation is very low (about 1 per cent), since most of the gamma photons pass through the gas without producing any ions. Most of the gamma photons which are counted have produced an electron from one of the walls of the tube by photo-emission.

Tubes for measuring the relative activity of samples of a liquid are often employed. Some types of Geiger tube dip into the liquid, whilst in the flow types the liquid flows through a glass tube which

passes through the gas mixture. In liquid sample tubes an annular sample of the liquid surrounds the gas filling of the Geiger tube. The minimum thickness of the glass wall separating the liquid sample from the gas filling is about 20 mg/cm² and therefore such tubes are not very suitable for counting beta emitters of maximum energy less than about 0·5 MeV.

QUENCHING

When a discharge passes through a Geiger tube, the positive ions, metastable atoms and ultra-violet photons formed may be capable of ejecting further electrons if they reach the cathode. Only those particles which have an energy exceeding the work function of the cathode material can cause an electron to be ejected from the cathode. In the case of positive ions, however, a free electron can be formed only if the energy of the ion exceeds twice the work function of the surface, since two electrons would have to be removed from the surface, one of which would neutralise the ion. Electrons emitted from the cathode on the arrival of a particle can cause spurious discharges, but this is prevented in modern Geiger tubes by the addition of a quenching gas.

Organically quenched tubes contain a few per cent of a polyatomic vapour such as ethyl alcohol or ethyl formate in addition to the main filling gas which undergoes ionisation (often argon or neon). Any positive inert gas ions, metastable atoms of the inert gas or ultra-violet photons give their energy to molecules of the organic vapour which is thus turned into other chemicals. An organic quenching agent gradually disappears from the gas mixture and the life of such tubes is limited to about 10^9 counts.

Another method of quenching a Geiger tube involves the addition of a small amount of a halogen vapour to the gas mixture. Bromine is normally used, since it is less reactive than chlorine, whilst the vapour pressure of iodine is insufficient at temperatures below about 0°C. Bromine molecules absorb ultra-violet photons and can take energy from inert gas ions or from metastable atoms. The molecules of bromine may be split into separate atoms, but in due course these atoms will recombine; the amount of bromine does not therefore decrease as the tube is used. Halogen quenched tubes tend to have a longer life than organically quenched tubes. Bromine ions reaching the cathode will not normally cause secondary emission.

Organically quenched tubes require much greater operating voltages than halogen quenched tubes. Most organically quenched tubes operate in the range 1,100 to 1,500 V, whereas most halogen

quenched tubes require about 400 to 700 V. Organically quenched tubes are often permanently damaged by the application of an excessive potential or of the correct potential applied with a reversed polarity. However, halogen quenched tubes are not normally affected for more than a short time by such treatment. The output pulses from halogen quenched tubes tend to be somewhat larger than those from some organically quenched tubes.

Ultra-violet photons formed in the discharge are absorbed by the quenching vapour (either organic or halogen) before they have moved very far from the point at which they are generated. Ions are thus formed at a point near to the discharge and it is this process which enables the discharge to spread along the anode wire. The high speed at which the discharge spreads is attributed to the fact that only photons and electrons take part in this photo-ionisation process; these particles move at a very high speed. In a proportional counter tube the discharge can occur at a localised spot near the anode, whereas in a Geiger tube it spreads along the whole length of the anode wire.

GEIGER TUBE PLATEAU

If a source of radiation is placed at a constant distance from a Geiger tube so that the rate of entry of the particles into the gas is constant, the type of curve shown in Fig. 8.3 will be obtained if the potential applied to the tube is slowly increased. At applied voltages smaller than the starting voltage, V_s, the output pulses from the tube are too small to be counted by the counting equipment used. A further increase in the applied potential causes the counting rate to increase very rapidly until the plateau threshold voltage, V_t,
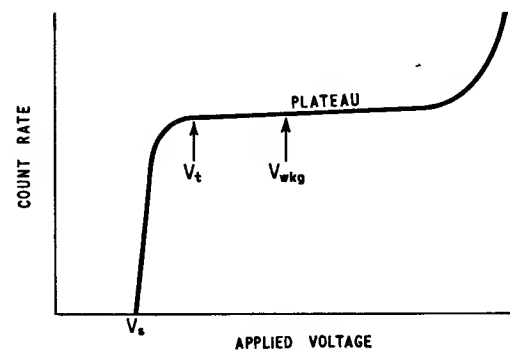
Fig. 8.3. A Geiger tube plateau.

is reached. The counting rate is not very dependent on the applied voltage in the plateau region, but increases rapidly at applied voltages above that corresponding to the upper end of the plateau.

The plateau has a slight slope. At one time this was attributed to an increase in the number of spurious pulses with applied voltage due to the quenching process not being fully efficient. However, it is now believed to be due to a slight increase in the active volume of the tube with the applied voltage. At higher applied voltages electrons formed beyond the end of the anode wire will be attracted to the latter and initiate a discharge.

The length of the plateau should not be less than about 150 V and the slope should be as small as possible. In a typical case the counting rate might increase by 0·05 per cent for each additional volt applied to the tube in the plateau region.

The working voltage of an organically quenched tube may be taken as about $(V_t + 100)$ volts and that of a halogen quenched tube as $(V_t + 60)$ volts, but these values are not critical. The plateau of an organically quenched tube should be plotted periodically to ensure that the performance is still satisfactory. As the quenching vapour is consumed, the threshold voltage tends to rise and the length of the plateau decreases.

CIRCUITS

The simple circuit of Fig. 8.2 may be used with an organically quenched tube, the resistor being about 10 MΩ and the capacitor about 100 pF. The output pulses can be fed into a suitable valve or transistor circuit. In the case of a halogen quenched tube, however, the anode load resistor should be divided into two parts and the output pulses should be taken from the junction of these resistors. The use of a split anode load circuit results in a reduced stray anode capacitance. The plateau characteristics of some halogen quenched tubes are adversely affected by stray anode capacitance; even a few picofarads can make an appreciable effect.

Geiger tubes are often connected to a quenching probe unit. When the Geiger tube produces an output pulse, the quenching probe unit feeds a negative going pulse of known duration to the anode of the Geiger tube to render the tube insensitive for a time longer than the dead time of the tube. The dead time of the system is thus equal to the length of the pulse from the quenching probe unit. Although this increases the dead time and, therefore, increases the number of pulses missed, it gives the dead time a definite value and enables correction to be made for the missed pulses. The dead

time of a Geiger tube itself is rather indeterminate and varies with the age of the tube.

HYSTERESIS

Geiger tubes show an effect known as 'hysteresis', although it is not really a hysteresis effect at all. When a tube has been counting at a high rate for a time, it will count at a rate much above the background rate after the radioactive source has been removed. The background rate falls to the normal value after a time. This effect is presumably caused by the presence of large numbers of excited atoms producing spurious pulses. Geiger tubes should not therefore be used to measure a relatively low counting rate immediately after they have been counting at a high rate.

Photoemission can occur from the cathodes of some Geiger tubes. Whilst this effect does not normally cause trouble, it can result in spurious counting in tubes which contain a mica or glass window. Some tubes have an end window coated with a very thin layer of graphite in order to exclude external light, whilst some manufacturers state that their tubes are not photosensitive.

The curve of Fig. 8.1 suggests that Geiger tubes require a greater potential than proportional counter tubes. Whilst this is true for a tube of specified geometry and gas filling which can be operated in either the proportional or the Geiger region, most proportional counter tubes are designed for beta counting at potentials of the order of 1,600 V. This is slightly higher than the operating potentials of most organically quenched Geiger tubes and considerably higher than the potentials required by most halogen quenched Geiger tubes.

SUGGESTIONS FOR FURTHER READING

S. A. KORFF AND H. KALLMAN, 'Electron and Nuclear Counters', Van Nostrand, London (1955).

J. B. DANCE, 'Electronic Counting Circuits', Iliffe, London (1967).

9

High Current Tubes

High current gas filled tubes operating in the arc discharge region of the characteristic are used mainly as switching devices for handling high power pulses and as sources of short but very intense light flashes. Both switching and flash tubes operate under pulsed conditions at high currents (often thousands of amps), but another type of tube, the Cerberus 'Arcotron', is capable of controlling a continuous current of a few amps and peak currents of over a hundred amps.

If a tube which has been designed to operate in the glow discharge region is operated at a high current, an arc discharge will be formed and the tube cathode will be destroyed. In the arc discharge region the current density is typically some hundreds of amps per square centimetre.

SWITCHING TUBES

Arc discharge switching tubes are used for a very wide variety of applications. These applications include, for example, protection devices in high voltage circuits, in the ignition system of Wankel rotary engines and as switches for discharging the delay line in pulse series modulators.

High current switching tubes can be designed so that the voltage drop across the tube (and hence the power dissipated in it) is relatively small. High voltage switching tubes of this type thus have a very high switching efficiency, but do not emit a great deal of light. The total voltage drop across the tube is the sum of the cathode fall (about 20 V) and the voltage drop across the plasma; the latter is kept small in high efficiency switching tubes.

DIODES

Some arc discharge switching tubes are diodes which do not conduct until the potential applied across them exceeds the breakdown voltage. Such tubes can be used as devices for protecting components against high voltage surges. For example, they may be
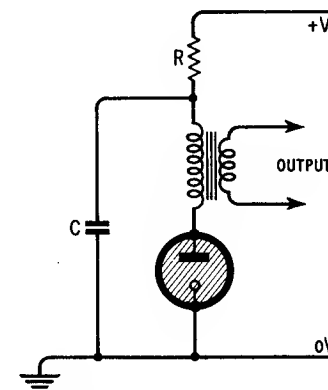
Fig. 9.1. A high voltage pulse generator.

used for the protection of the series capacitors used for power factor correction on high power transmission lines. If the voltage across the capacitor (normally 500 to 800 V on an 11 kV line) rises, the diode connected across the component will conduct and prevent the capacitor from breaking down. Such diodes are known as spark gaps or as surge diverters.

Arc discharge diodes are also used for the protection of telephone lines against the over-voltages which may arise from lightning discharges, accidental contact with power lines, static charges, etc. It is usual to connect one of the diodes from each line to earth and a diode with a lower striking voltage between the two lines. The latter diode prevents an excessive voltage from being formed across any apparatus connected to the line.

High current diodes can be used in the type of circuit shown in Fig. 9.1 for the generation of high voltage pulses; the output may, for example, be used for supplying power to an electric fence. The capacitor charges through the resistor until the diode breaks down. The capacitor then discharges through the transformer and a high voltage output pulse is produced across the secondary winding. The capacitor then recommences to charge and the cycle is repeated once again.

ARC DISCHARGE TRIGGER TUBES

Arc discharge trigger tubes contain three or four electrodes. As in the case of the glow discharge trigger tube, the main anode to cathode gap is made to conduct by the application of a suitable potential to a trigger electrode. A number of different designs of tube are available. In some types of tube the trigger electrode consists of a wire placed in a hole drilled in one of the two hemispherical electrodes which form the main gap. The application of a trigger pulse effectively converts the discharge gap from two hemispheres to a point and a hemisphere.

The S.T.C. 'Trigatron' tube has been designed for the discharging of a delay line in pulse series modulation circuits. The trigger electrode is a tungsten wire projecting from a hole drilled in a
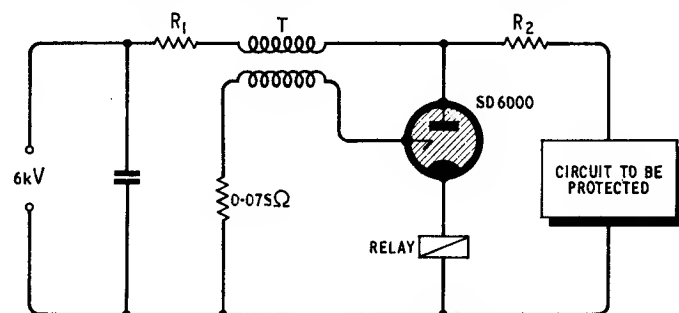
Fig. 9.2. A protection circuit using the SD6000 surge diverter.

hemispherical molybdenum anode. An argon gas filling at a pressure of 3 to 4 atm is employed—the tube being covered in a woven material cemented to the glass envelope to limit the amount of flying glass in the event of the tube bursting. The tube requires triggering pulses of a few kilovolts in amplitude and of the order of a microsecond in duration. It can control peak output powers of about 150 kilowatts at pulse repetition rates of about 1,000 pulses per second.

The G.E.C. surge diverter type SD6000 employs a mercury cathode, but a metal such as barium is added to the mercury in order to reduce the work function of the surface and thus enable the tube to function with trigger currents of about 100 mA instead of about 1 A. The tube will not conduct in the absence of a trigger potential if the potential applied across the main gap is less than about 6 kV.

The type of circuit in which this tube may be used is shown in Fig. 9.2. The non-inductive resistors R_1 and R_2 have values of a

few ohms each. R_1 limits the current passing through the surge diverter, whilst R_2 is employed to ensure that the anode voltage of the surge diverter will not fall to zero if a short circuit develops across the protected circuit.

If the current flowing to the protected circuit suddenly increases so that the triggering pulse from the ringing transformer, T, exceeds 2 kV, the main gap of the surge diverter will breakdown within 0·2 μsec. The reservoir capacitor discharges and the relay in the diverter cathode circuit breaks the main power supply line. The supply can be restored very quickly. This type of circuit is very useful for the high speed fault protection of radio transmitters.

STROBOSCOPE TUBES

Stroboscope tubes usually have an internal triggering electrode, but the anode to cathode gap is large enough for the tube to emit flashes of a reasonable intensity. The so called 'Strobotron' tube employs an auxiliary anode which is placed much nearer to the cathode than the main anode. A potential of about +100 V is normally applied to the auxiliary anode. The trigger electrode is a wire probe passing into the cathode. Each time the tube is triggered, a capacitor discharges through the main gap.

FLASH TUBES

In flash tube circuits for photographic and other purposes, a capacitor is discharged through the tube so that an intense flash of light is emitted from the ionised gas. The flash tubes contain two internal electrodes, the anode and the cathode; the trigger electrode consists of a wire wound around the outside of the tube. The gas filling is normally argon, krypton or xenon or a mixture of these gases; it may be chosen so that the spectral energy distribution is very similar to that of daylight. Some flash tubes are straight, but others are U shaped or in the form of a helix. These two latter forms enable compact tubes to be constructed which have an arc length great enough for the operating efficiency to be high.

The type of circuit in which a flash tube is used is shown in Fig. 9.3. When the switch S_2 is closed, the capacitor C_2 commences to charge through R_3. C_1 also commences to charge to a lower voltage. When both of these capacitors are charged, the tube may be fired by closing S_1. The capacitor C_1 discharges through the primary winding of the transformer and a pulse of a few kilovolts
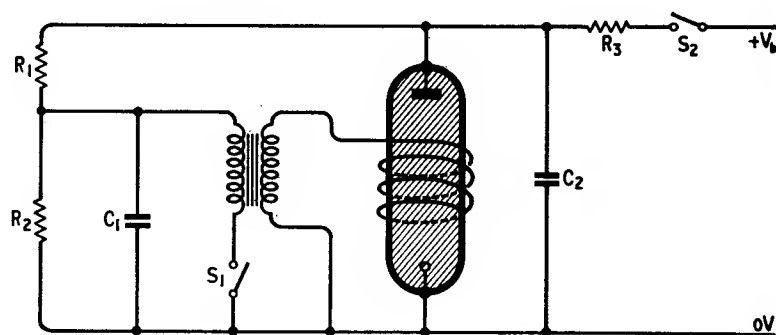
Fig. 9.3. A flash tube circuit.

is produced across the secondary winding. This is applied to the external trigger electrode. The capacitive coupling through the glass of the tube distorts the electric field so much that enough ions are formed to initiate a discharge. The discharge quickly passes through the glow mode to the arc mode of operation. When C_2 has almost discharged, the current passing through the tube falls to zero.

The anode operating potential of the flash tube immediately before a current flows is usually in the range 250 to 4,000 V, depending on the type of tube. The tube behaves as a resistance of the order of $1\,\Omega$ in value and a large current, therefore, passes from the capacitor C_2. The duration of the flash is normally within the range 0·02 to 2 msec.

The energy stored in a charged capacitor is $\frac{1}{2}CV^2$ where C is the capacitance value in farads and V is the voltage across the capacitor. If the anode potential of the tube before striking is V_1 and the anode extinction voltage is V_2, the energy delivered to the flash tube, E, is the difference between the initial and final amounts of energy stored in the capacitor, that is:

$$E = \tfrac{1}{2}CV_1^2 - \tfrac{1}{2}CV_2^2 = \tfrac{1}{2}C(V_1^2 - V_2^2)$$

V_2 is usually of the order of 20 V and V_2^2 is, therefore, normally negligible in comparison with V_1^2. The instantaneous power passed to the tube may exceed 1 MW.

As the energy per pulse passed to the tube is increased, the light output increases more than in direct proportion to the increase in the amount of energy. For a given value of capacitor and applied voltage, the amount of light emitted in successive flashes is very constant, but the first flash of a series is usually of a somewhat lower intensity. Overall efficiencies of about 50 lm/W are obtainable.

The American term 'flash lamp' is, incidentally, synonymous with the English term 'flash tube'; it has a meaning which is very different from the English term 'flash lamp' which is a hand torch.

LASERS

Doped crystal lasers employ flash tubes, whilst gas lasers are a special form of discharge tube. In both types light amplification occurs by a process of stimulated emission.

The laser is a device which was first developed about 1960 for the production of a coherent beam of light (that is, a beam of light in which all of the waves have the same plane of polarisation and are all in phase). Lasers have quickly passed from the laboratory stage to the point at which they are a very useful tool in many applications such as range finding, micro-welding apparatus and medicine.

The word laser is an acronym for 'Light Amplification by the Stimulated Emission of Radiation' (although some laboratories order lasers as if it meant 'Lolly Acquisition Scheme for Expensive Research'!). Light amplification by stimulated emission occurs when a photon interacts with an excited atom so that an additional photon identical with the incident photon is emitted from the atom. The two photons travel in the same direction, have the same phase and the same plane of polarisation. The laser process can occur only if the loss of an amount of energy almost exactly equal to the energy of the incident photon will leave the atom in one of its possible energy states.

The two photons resulting from the stimulated emission process may each undergo further amplification if they strike excited atoms. The amplification process can thus continue provided that enough excited atoms are available and provided that the photons are not absorbed. Atoms in the lower energy state will absorb any of these photons to form excited atoms, since such photons have just the correct amount of energy to raise the atoms to the excited state. Amplification will predominate over absorption only if the number of excited atoms in the laser material is greater than the number of atoms in the lower energy state.

Energy must be fed to the atoms of the laser material to enable this condition to be satisfied. The process of putting energy into the system is known as 'pumping', since the atoms are said to be 'pumped' into a higher energy level. It can be shown that pumping cannot be effected by merely heating the material; in the ruby laser the light from a flash tube supplies the pumping energy, whilst in the gas laser the energy comes from the electrical discharge.

In a practical laser most of the light leaving the ends of the laser material must be reflected back so that it undergoes further amplification. Only in this way can a powerful output beam be produced. The mirror at one end of the laser material allows a small proportion of the incident light to pass through it and it is this light which constitutes the output beam.

DOPED CRYSTAL LASERS

A number of very different types of laser have been produced. One of the best known types is the ruby laser which is a form of
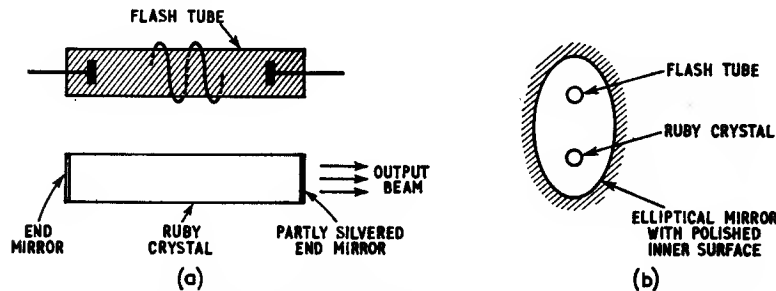
Fig. 9.4. (a) A ruby laser (the elliptical mirror is not shown); (b) a cross section through a ruby laser showing the elliptical mirror.

doped crystal laser. A large ruby crystal in the form of a rod is employed. Ruby consists of aluminium oxide doped with a small percentage of chromium oxide; it is the latter which acts as the laser material.

The ruby crystal is usually placed at one of the foci of an elliptical mirror and a powerful flash tube at the other focus. It is a property of elliptical mirrors that any light emitted from one focus is reflected to the other focus. Thus almost all of the light from the flash tube passes to the ruby crystal (see Fig. 9.4). However, some low power ruby lasers do not employ elliptical mirrors. The light from the flash tube supplies the pumping energy.

Any stray photons of the correct wavelength present in the ruby crystal will be amplified by the laser action. A powerful pulse of red light will be emitted from the partially transmitting end mirror. The wavelength of this light is 6,943 Å and the pulse duration typically 1 msec. The light pulse may have a power level of over 1 MW in a large laser; such beams may be used to burn a small hole through a steel plate of $\frac{1}{4}$ in. thickness if they are suitably

focused. The beams from ruby lasers may also be used in the medical field, e.g. for 'welding' detached retinas back into place.

Doped crystal lasers using other types of laser material can produce pulses of light in the near or far infra-red regions of the spectrum. The efficiency is usually a few per cent. All doped crystal lasers generate large amounts of heat; a limit must therefore be imposed on the flashing rate and on the input power per pulse.

GAS LASERS

The commonest form of gas laser employs a glass or quartz tube about one metre long containing a mixture of about 10 parts of helium to 1 part of neon. The pressure is about 1 mm of mercury. The pumping energy may be derived from a radio frequency discharge of about 100 W input power at a frequency of perhaps 30 Mc/s, but gas lasers with heated cathodes can be made for operation from direct current. The helium atoms are raised to a metastable level and pass their energy to the neon atoms; the latter take part in the laser action.

Special mirrors coated with many layers of materials of suitable refractive indices must be employed in gas lasers, since the amplification is quite small. Such mirrors reflect about 99 per cent of the light of one particular wavelength which is incident upon them. If the end mirrors are placed outside the discharge tube for ease of adjustment, windows cut to the Brewster angle must be placed at each end of the tube to minimise losses by reflection.

Helium-neon gas lasers are often operated in the red region of the spectrum at 6,329 Å, but they can also be used in the near infrared at 11,523 Å or in the far infra-red at 33,913 Å. The type of coatings on the mirrors used determine the output wavelength.

The output of a gas laser can be continuous (typically 50 mW), whilst that of a ruby laser is pulsed. The light from a gas laser is more nearly monochromatic than that from any other source, since the bandwidth can be made less than 1 c/s.

Gas lasers are used in range finding and in interferometry; they may also find applications in communications (e.g. between artificial satellites) and are important research tools.

ARCOTRONS

The Cerberus 'Arcotron' tubes were introduced in 1961 for the switching of continuous currents up to several amps. The principle

of operation of these tubes is very similar to that of the glow thyratron described in Chapter 4. Ions are generated in an auxiliary arc discharge which is maintained between the cathode and a perforated auxiliary anode; the latter corresponds to the electrode marked K in Fig. 4.1. The control grid and the anode are in the same relative positions as in the glow thyratron of Fig. 4.1.

When the grid of an Arcotron is maintained at a suitable negative potential, the electrons which pass through holes in the auxiliary anode are repelled as they approach the grid. If the negative grid voltage is removed, however, electrons from the auxiliary discharge pass through the grid and initiate the main discharge.

A number of Arcotron tubes have been produced with different ratings. They may be used for the control of the amount of heat developed in an electric heating element. Simple circuits operating directly from the a.c. mains supply have been designed by the manufacturer of the tubes. The Arcotron main gap is connected in series with the heating element across the mains supply. A conducting tube is automatically extinguished during the alternate half cycles of the mains supply voltage. One circuit incorporates a compensating system which enables the power dissipated in the load to remain constant if the mains voltage changes.

Arcotron tubes are no longer recommended for use in equipment being designed at the present time and, therefore, they will not be discussed further. One of the disadvantages of the Arcotron is the fairly high value of the potential drop across a conducting tube (about 20 V); this is considerably more than the voltage drop across a silicon controlled rectifier and the latter is, therefore, a more efficient switch.

SUGGESTION FOR FURTHER READING

P. M. MURPHY AND H. E. EDGERTON, 'Electrical characteristics of stroboscopic flash lamps', *J. Appl. Phys.*, **12**, *12*, 848 (1941).

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